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Research Support for the Analysis and Management of Celestial Backgrounds Data

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22 September 2000

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13. ABSTRACT *(Maximum 200 words)*
TerraSystems, Inc. (TSI) supported the validation and analysis of celestial backgrounds data collected by various sensors (including MSX) and assisted in incorporating the results of these analyses into improved computer models which were then integrated into existing Celestial Backgrounds codes. The results of this activity will improve the quality of the data and the ability to accurately simulate and predict the behavior of the infrared environment on operational spaced borne systems. TSI's effort included: (1) methods of improving the quality of collected data through error analysis and post-event correction, especially with respect to removing known and unknown asteroids from the MSX point and source list and improving the celestial background asteroid model with new sources of data from SIMPS, ISO, and polarimetry and (2) developing techniques useful in promoting collaborative analysis by geographically dispersed teams either in small groups or at large, topical meetings.

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1 INTRODUCTION

Several different kinds of support were provided under this contract. These can be broken down into the following general tasks: 1) Technical support for MSX Celestial Background Team program related activities, including meetings and presentations, 2) MSX Celestial Background Team web site development and maintenance, 3) Research regarding the contribution of asteroids to the celestial background, primarily at mid-infrared wavelengths (8 to 30 μm), and 4) Publication of portions of the work done under task 3.

An overview of the activities performed under these four tasks is presented in the remainder of this section and a more detailed presentation of results obtained under task 3 is given in subsequent sections. Although approximately equal time was devoted to tasks 1, 2, and 3+4 the amount of space devoted to tasks 1 and 2 in this report is much less than that devoted to tasks 3 and 4. This is because, while the support provided under tasks 1 and 2 was time consuming, these tasks produced little in the way of long-term deliverables.

1.1 Technical Support, Meetings, and Presentations

During most of the contract's period of performance the PI attended bi-weekly Configuration Control Board (CCB) meetings at Hanscom AFB as scheduled by AFRL/VSBC. He also represented the MSX Celestial Backgrounds PI on bi-weekly MSX status teleconferences, especially whenever the latter was unable to participate.

As directed, he created and submitted to the AMSC, Celestial Backgrounds PI Analysis Notes for the team's DCEs.

He attended the NASA – AFSPC NEO Working Group meeting at MIT/LL on 17 September 1998. He wrote and presented one paper (Tedesco *et al.*, 1998) and co-authored a second (Egan *et al.*, 1998) at the Division for Planetary Sciences Meeting in Madison, WI, 10 – 15 October 1998.

1.2 MSX Celestial Background Team Web Site

Web sites, by their very nature, are dynamic. Thus, the site at the time the reader of this document accesses it will likely bear little resemblance to that created under this contract. For this reason, only a high-level overview of the creation and development of the MSX Celestial Background Team web site will be described here.

The MSX CB Web Site was created with a Navigation frame on the left, a webmaster contact and last updated footer, and a main frame in the remainder of the page. All pages linked to from within the site displayed in the main frame. The Navigation frame contained buttons labeled: Home, Overview, Team, Results, Highlights, Data, MSX Time, and Links. The Home button returned the viewer to the home page, shown in Fig 1. Figures 2 through 8 show each of the pages reached from the navigation buttons.

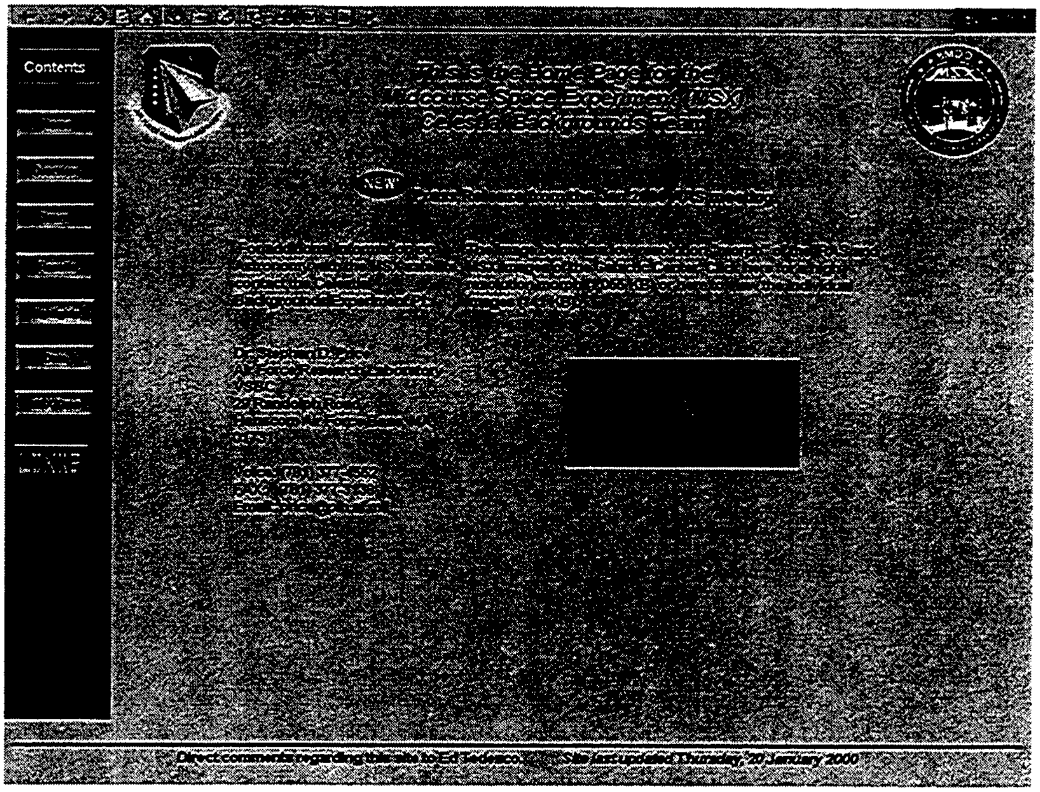


Figure 1. 20 Jan 2000 version of MSX Celestial Backgrounds Team web page.

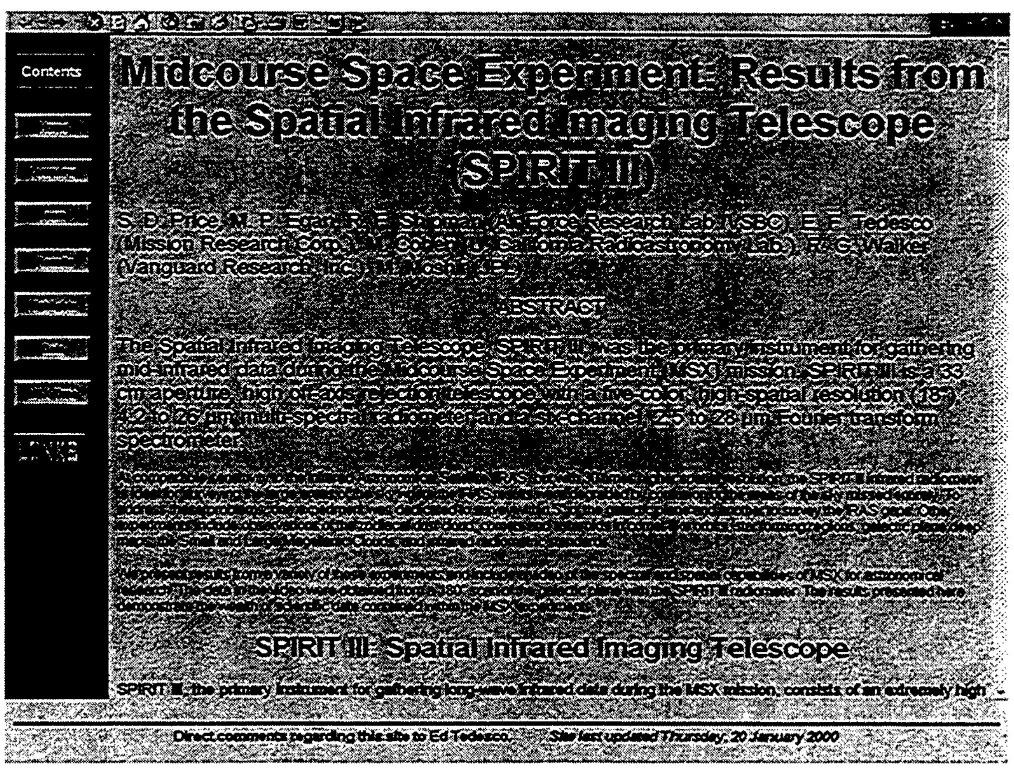
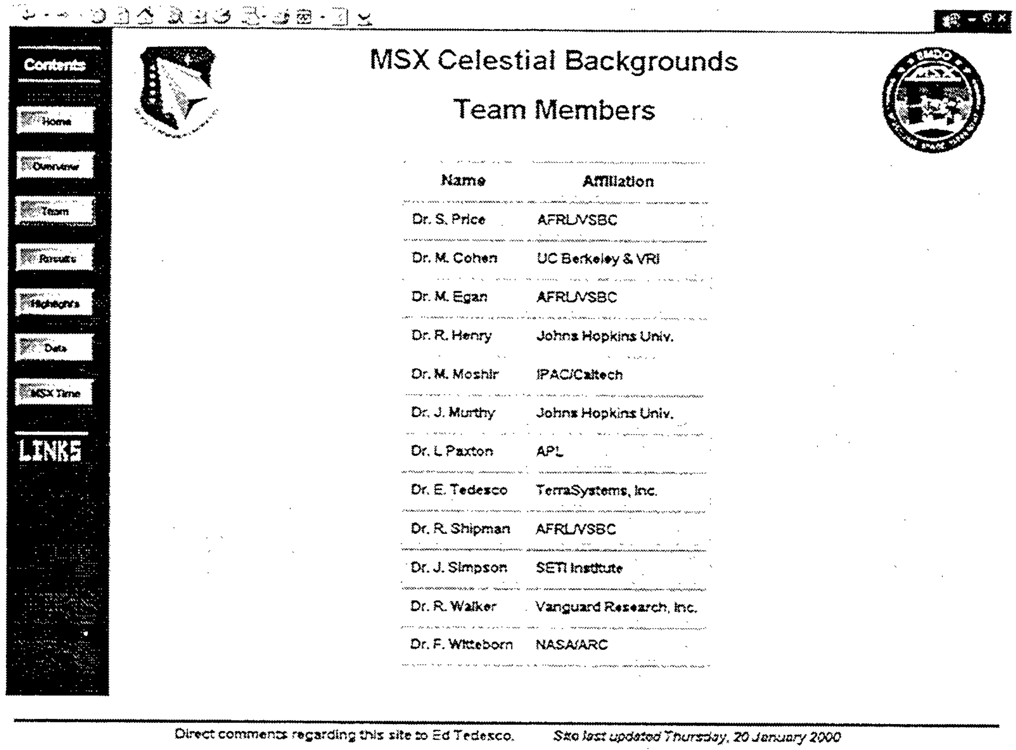


Figure 2. Overview.



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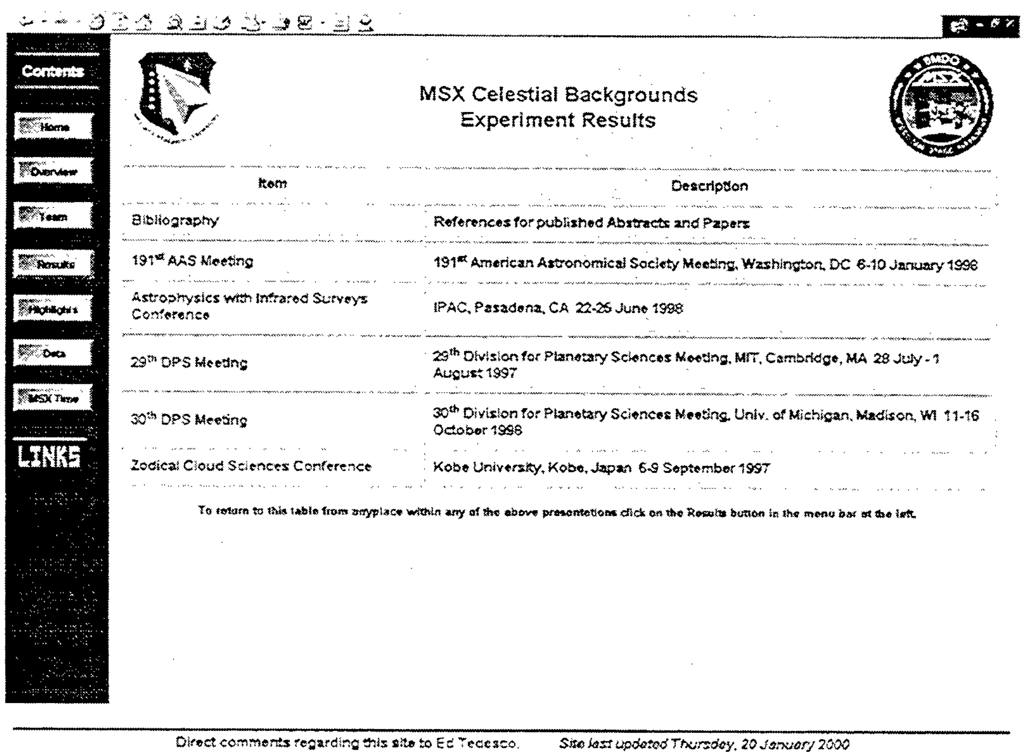
Dr. R. Walker	Vanguard Research, Inc.
Dr. F. Witteborn	NASA/ARC

Direct comments regarding this site to Ed Tedesco. *Site last updated Thursday, 20 January 2000*

Figure 3. Team.



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Item	Description
Bibliography	References for published Abstracts and Papers
191st AAS Meeting	191st American Astronomical Society Meeting, Washington, DC 6-10 January 1998
Astrophysics with Infrared Surveys Conference	IPAC, Pasadena, CA 22-26 June 1998
29th DPS Meeting	29th Division for Planetary Sciences Meeting, MIT, Cambridge, MA 28 July - 1 August 1997
30th DPS Meeting	30th Division for Planetary Sciences Meeting, Univ. of Michigan, Madison, WI 11-16 October 1998
Zodical Cloud Sciences Conference	Kobe University, Kobe, Japan 6-9 September 1997

To return to this table from anyplace within any of the above presentations click on the Results button in the menu bar at the left.

Direct comments regarding this site to Ed Tedesco. *Site last updated Thursday, 20 January 2000*

Figure 4. Results.

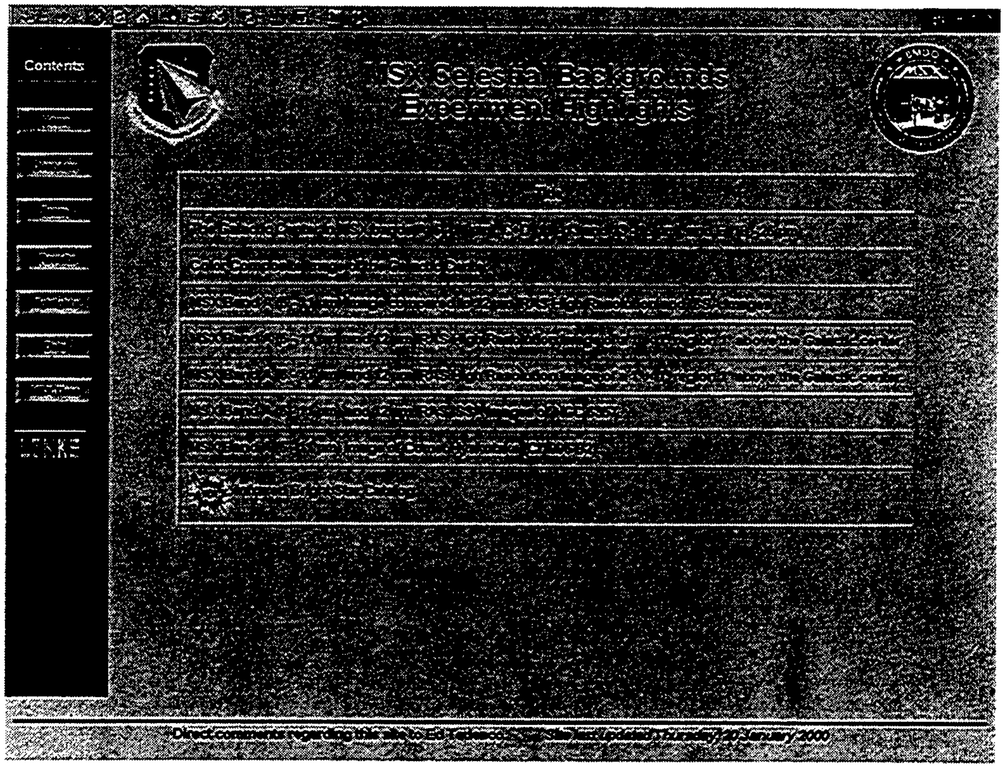


Figure 5. Highlights.

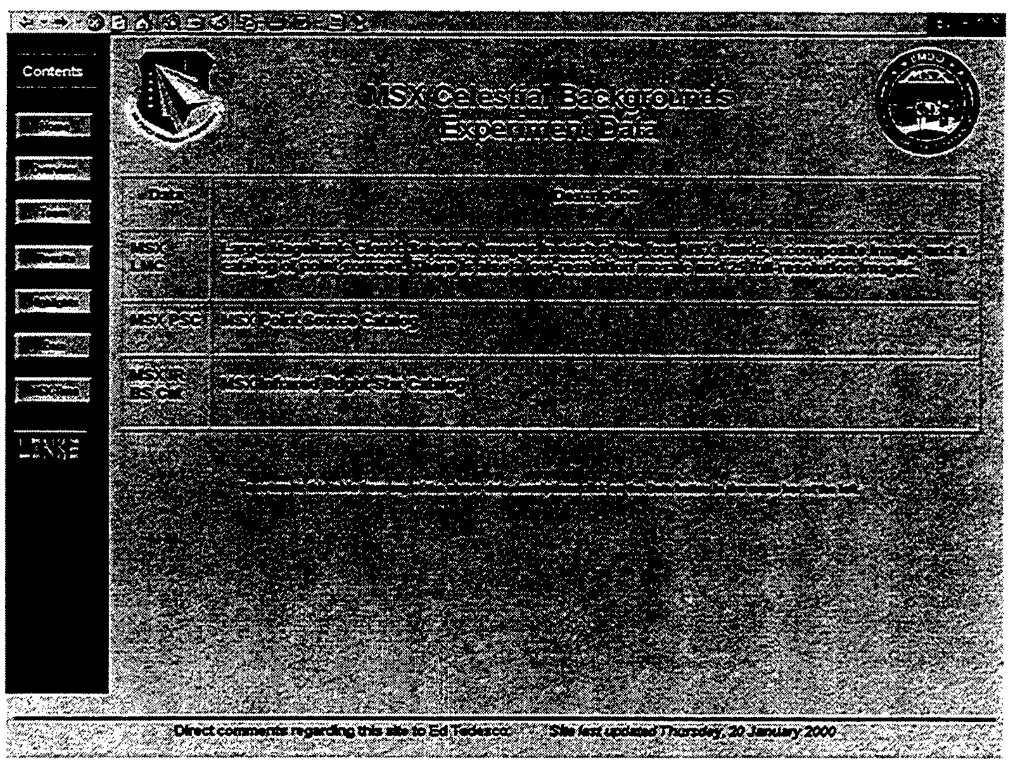
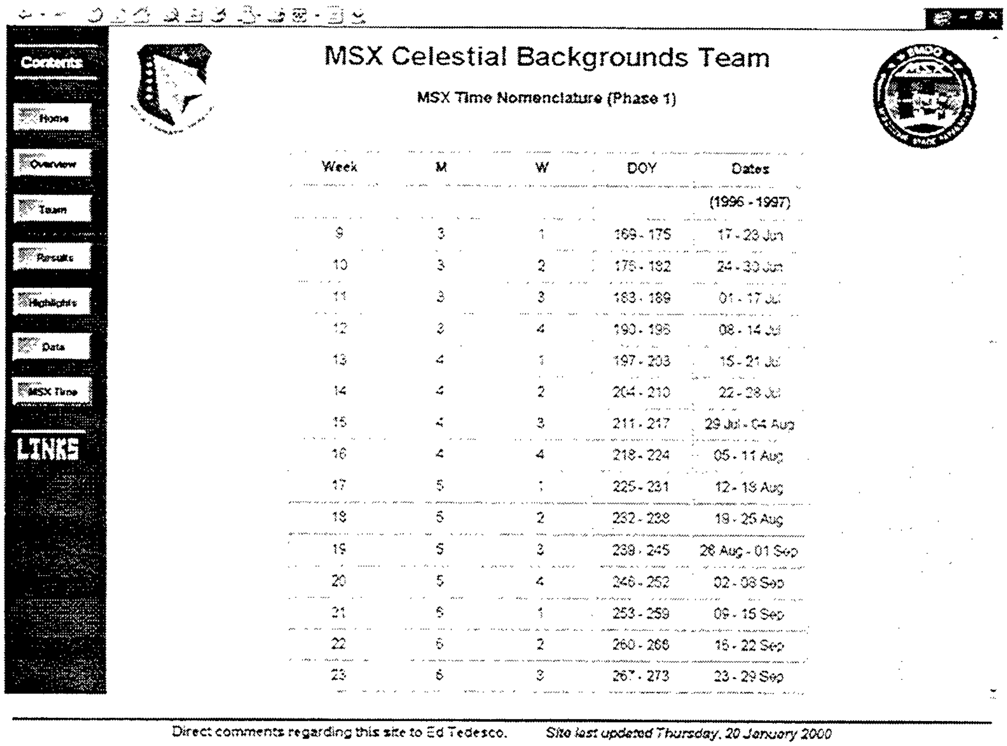


Figure 6. Data.



Week	M	W	DOY	Dates (1996 - 1997)
9	3	1	169 - 175	17 - 23 Jun
10	3	2	176 - 182	24 - 30 Jun
11	3	3	183 - 189	01 - 07 Jul
12	3	4	190 - 196	08 - 14 Jul
13	4	1	197 - 203	15 - 21 Jul
14	4	2	204 - 210	22 - 28 Jul
15	4	3	211 - 217	29 Jul - 04 Aug
16	4	4	218 - 224	05 - 11 Aug
17	5	1	225 - 231	12 - 18 Aug
18	5	2	232 - 238	19 - 25 Aug
19	5	3	239 - 245	26 Aug - 01 Sep
20	5	4	246 - 252	02 - 08 Sep
21	6	1	253 - 259	09 - 15 Sep
22	6	2	260 - 266	16 - 22 Sep
23	6	3	267 - 273	23 - 29 Sep

Figure 7. MSX Time.

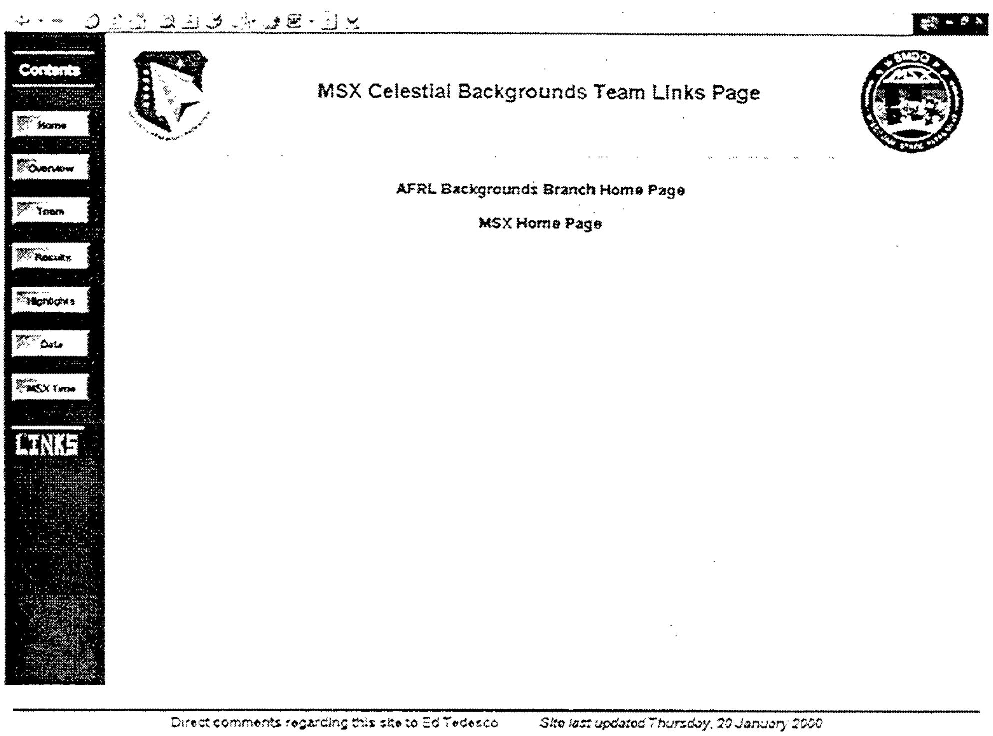


Figure 8. Links.

1.3 Research on Asteroid Contribution to the Celestial Background

This task consisted primarily of two subtasks: Task 3.1 – Production of a PC version of the IRAS Minor Planet Survey database (SIMPS) and Task 3.2 – development of an Asteroid Statistical Model (ASM). A third sub-task, creation of an MSX Asteroid Catalog, was begun and numerous asteroids identified in the MSX Celestial Backgrounds team data. Some of these results have already been published (Egan *et al.*, 1998). However, because the final MSX point source list was completed too late to allow a through validation during the period of performance of this contract, this task will be completed under funding provided by the National Science Foundation (NSF) to the PI of this contract, and with Drs. M. Egan and S. Price of AFRL/VSBC at Hanscom AFB as co-investigators. Work under this NSF grant, which also includes publication in the refereed literature of the results of the SIMPS task, will begin in October 2000.

The results from SIMPS were used in creating the Asteroid Statistical Model. The ASM was delivered in September 1999 for incorporation into the Celestial Background Scene Descriptor (CBSD) code.

Task 3.1 will be discussed in depth in §2 [THE SUPPLEMENTAL IRAS MINOR PLANET SURVEY (SIMPS)] and Task 3.2 in §3 [THE ASTEROID STATISTICAL MODEL (ASM)].

1.4 Publications

The PI's portion of the work involved in producing the following publications was supported under this contract:

Cellino, A., Di Martino, M. Egan, M. Price, S. D., Tedesco, E. F. (2000). Space-based infrared/visible telescope to study small solar system objects. *Proceedings of SPIE* Vol. 4013, pg. 68. Astronomical Telescopes and Instrumentation 2000 session on UV, Optical, and IR Space Telescopes and Instruments, 29-31 March 2000 in Munich, Germany.

Egan, M.P.; Price, S. D.; and Tedesco, E. F. (1998). Infrared Detection and Characterization of Near Earth Objects. *Bull. American Astron. Soc.* **30**, #16.05

Sykes, M. V.; Cutri, R. M.; Fowler, J. W.; Tholen, D. J.; Skrutskie, M. F.; Price, S.; Tedesco, E. F. (2000). The 2MASS Asteroid and Comet Survey. *Icarus* **146**, 161-175.

Tedesco, E. F.; Muinonen, K.; Egan, M.P.; and Price, S. D. (1998). Discovery of Aten Asteroids: Visual Ground-Based vs. Infrared Space-Based. *Bull. American Astron. Soc.* **30**, #16.06

Tedesco, E. F.; Muinonen, K.; Price, S. D. (2000). Space-based infrared near-Earth asteroid survey simulation. *Planet. Space Sci.* **48**, 801-816.

Appendix 1 contains reprints of the above publications except those for Cellino *et al.* (2000) and Sykes *et al.* (2000), which were not available at the time this report was prepared. Instead, the abstract from the published paper is included. The work published in the *Bull. American Astron. Soc.* are abstracts of papers presented at meetings of the Division for Planetary Science of the American Astronomical Society for which conference proceedings are not published.

2 THE SUPPLEMENTAL IRAS MINOR PLANET SURVEY (SIMPS)

SIMPS is an all-microcomputer code version of IMPS, the IRAS Minor Planet Survey (Tedesco, 1992), which was also produced under AFRL funding. IMPS itself was a port of the code used to produce the first version of an IRAS Asteroid catalog (Matson, 1986). The first port was necessary for two reasons: 1) technical issues regarding ground-based data used in processing the IRAS asteroid data and recognition of several systematic effects which had been introduced into the 1986 version, and 2) the replacement of the original computer on which all IRAS data had been processed (an IBM 3030) with a Cyber 3600 together with the decision by the IRAS project that the asteroid code would not be ported to the new computer. Thus, between 1988 and 1992, the IRAS asteroid database and code were ported to the IPAC Cyber. Microcomputers of the time (Intel 8 MHz 80386 CPU, 64 KB memory, and 10 MB hard drives) were too limited to allow them to be used to perform the association portion of the task. However, such machines were adequate to process the associated sources output by the Cyber. Thus, a hybrid system was created which used the Cyber to make the associations and an 80386 CPU microcomputer to use the Cyber's output to perform validation tasks and derive diameters and albedos for the asteroid sources. (See Matson and Tedesco, 1992, especially §2.7, for further details.)

2.1 SIMPS Recoding

Toward the end of the IMPS task, in 1992, IPAC retired the Cyber, replacing it with a system of distributed workstations. Thus the IRAS asteroid association code was again orphaned. Hence, in 1992, during the last few weeks of the IMPS task, the Cyber-specific code was converted to Microsoft FORTRAN 77 and validated by running it on a small subset of orbital elements. This set of microcomputer codes, numbering 50 in all (seven in FORTRAN and the remainder in Turbo Pascal) was the starting point for developing SIMPS.

In 1996, under Mission Research Corporation's CBSD task, it was decided to rerun the IMPS code. The primary reason for this decision was the realization that by mid-1996 the known asteroid population had increased by about 1,800 asteroids since publication of the IMPS catalog in 1992. (Between 1986 and 1992 the population increased by 1,361.) When the 1992 code was run (on a Gateway system using a 66 MHz 80486 CPU with 32 MB memory) it crashed. It would run on a set of 100 orbital elements but not on a set containing more than 1000 elements. The decision was made to repair the code. Thus, at a fairly low level-of-effort, between 1996 and the present this was done.

The first task was to get the original version to execute. This was accomplished by converting the seven FORTRAN and 43 Turbo Pascal codes to versions that would compile and execute on the compilers available at the time. As part of this task the IRAS asteroid database (IP01, a subset of about 2.7 million probable sources extracted from the IRAS Hours Confirmation Processor – see Fowler and Chillemi, 1992, §4.2) was written to CD-ROM. Paul Noah did the code conversion under the direction of Edward Tedesco. Following validation, the results (based upon an orbital element set containing 8,603 asteroids from the April 1998 Minor Planet Center) were incorporated into the CBSD model and used in creation of the Asteroid Statistical Model.

Based upon the above results it was decided to limit this and future processing to known asteroids as even those with so-called multi-opposition orbits were not of sufficient accuracy to permit reliable associations with potential IRAS sources.

A number of minor changes were incorporated into the current version. Namely: 1) incorporation of revised physical constants from Cohen and Taylor (1999; see http://physics.nist.gov/constants). For example, the value for the Stefan-Boltzmann constant has changed by –0.00011, *i.e.*, by 20 ppm. The new value is supposed to be accurate to 7 ppm; the accuracy of the previous value was 34 ppm. And, 2) Meg Noah found an error in how the time was converted from IRAS time to UT. The corrected code yields times differing by up to 8 seconds. Comparing the output of the corrected code with that of previous results showed that out of 260,780 bytes one byte differed (the diameter for asteroid 2813 Zappalà changed from 32.57 to 32.58).

When this code was next run, in July 1999, it blew up. This problem was traced to a bug in the Borland Turbo Pascal codes that use the CRT unit (required for all IO). When such codes run on CPUs faster than about 266 MHz they give a Runtime 200 error message during startup. The computers on which we last ran this code had 200 MHz processors; their replacements are 300 and 500 MHz systems. Although we found a work-around for this, see below, Borland, the maker of Turbo Pascal, no longer supports this product and does not sanction this work-around.

Below is the message relating to this problem, posted by Borland on their web site:

> *Runtime Error 200 - 'Divide by 0'*
>
> *Applications that use the CRT unit may generate this error message when running on very fast machines (i.e., Pentium Pro 180 and above). The cause of this error is a timing loop that occurs as part of the initialization of the CRT unit. This timing loop counts how many clock ticks occur within the loop and then that number is divided by 55. The result of this division is a value that is too large to fit into an integer value. The 'Divide by 0' error message is the catch-all error that is displayed when this overflow occurs.*

> *There are currently no Borland endorsed patches for this problem. There are several user provided patches available on the internet that patch both the CRT unit as well as existing EXE files. The easiest way to obtain these patches is to go to www.altavista.digital.com and search on '+ bp7patch.zip + tppatch.zip' without the quotes.*
>
> *These patches are not endorsed or supported by Borland and are used at your own risk.*

Eventually we found a patch (not one of those mentioned on the Borland site) and were able to get the SIMPS code to run. However, considering that this was not an acceptable solution, we proposed to the Air Force, and they approved, that the affected codes be rewritten in C++. The benefit of doing this now is that we have a working Turbo Pascal version with which to validate the C++ code and, upon completion of the conversion, the C++ code will be more efficient to run and maintain. The C++ version of the SIMPS codes is referred to as CSIMPS; its creation is described in the following section.

2.2 CSIMPS

The material in this section is adopted from a report prepared by M. Noah of Mission Research Corporation, the programmer responsible for translating the Turbo Pascal codes to C++.

In SIMPS, there were seven FORTRAN codes and 43 Turbo Pascal codes. Three of the FORTRAN codes (AKM.FOR, GENAK04.FOR, and GENAK09.FOR) were responsible for much of the former known asteroid (AK) processing, the remaining were the thermal model codes and time/log utilities. These codes run sequentially taking some outputs of the previous codes as inputs. Collectively, the files AK.Log, AK01, AK01Indx, AK02, AK13, AK04, IPUD, and AK09 are created by the FORTRAN routines. Four Turbo Pascal codes (GENAK06, GENAK05, GENAK10, and Add2AK10) created and modified AK06, AK07, AK05, and AK10, based on the previous files and system files from IPAC. Turbo Pascal codes performed the asteroid derived (AD) processing and the final product (FP) processing. These processors were not fully de-coupled, *i.e.*, some of the AD processing programs set flags and fields in the AK file output. Efforts have been made to make separate packages in the CSIMPS implementation.

The LIMISS code creates the AD06 file and updates the AK10 file in the following ways: 1) if (AK10Rec.AlbMst == 0.0) AK10Rec.AlbMst = 0.01, and 2) AK10Rec.PStatW = (AK10Rec.PStatW | 1024), sets bit 10. The ADLBH code creates the AD02 file. The GENFP01 process, which generates a FP01 file with all records initialized to 0s, must be run prior to the FPARD which populates the FP01 file with values and updates AD02's ADStat word, and AK05's AstatW word. The IMPSUT01 code updates the AstatW word in AK05 and the PstatW word in AK10. The IMPSUT01 code updates the PstatW word in AK10.

There are 10 Turbo Pascal codes that independently use the AK and AD outputs to produce final products. The programs GENAD07 and GENAD04 produce the AD07 and AD04 text files of asteroid derived parameters. The programs GENAK11 produce the AK11 text file, which is the only AK file not used in any subsequent processing. The programs GENFP20, GENFP21, GENFP102, GENFP105, and GENFP108 create the set of FP final products described in the IMPS Minor Planet Survey.

The fact that AK, AD, and AP processes all effected output associated with AK database files, and the fact that one of the static database inputs is preprocessed, made the system organization very intertwined, and the conversion to C++ code was more complex than need be.

The output files, with one or two exceptions are the same format for CSIMPS as for SIMPS. In order to be able to process more known asteroid ID numbers, some fields in some records needed to be changed from a short (2-byte) integer to a long (4-byte) integer. This necessarily made otherwise identical file records different.

The above run stream is summarized in Appendix 2. This documents the order in which the codes must be run to achieve the desired output.

2.3 SIMPS RESULTS

Using a 12,656 orbital element sample, the most recent set of elements received from the Minor Planet Center (in Nov 1999), SIMPS associated 2,083 different asteroids with IRAS sources. This is an increase of 280 (15.5%) over IMPS.

Figure 9 is a plot of the number of SIMPS asteroids per 100 numbered asteroids. While around 90% of the first few hundred asteroids have IRAS associations[1] this fraction drops sharply with increasing number to where only 3.5% of asteroids with numbers between 4679 and 12656 were detected by IRAS and only 1.0% of those with numbers above 11000.

Given the growth in the rate of increase of the numbered asteroids, as shown in Figure 10, the numbered population should reach about 25,000 by September 2001 and perhaps 50,000 a year later. (The numbered population reached 17,349 in September 2000.) If the one-percent-per-thousand detection rate continues to hold for this population, then we will find an additional few hundred asteroids with IRAS associations in the 50,000 numbered asteroid element set.

Tabulated results for the new SIMPS asteroid associations are given in Appendix 2. SIMPS RESULTS.

[1] The IRAS survey of the main asteroid belt's phase space was about 94% complete. Because of their slower motion this increased to ~98% for the Jupiter Trojan asteroids. (See Tedesco *et al.*, 1992.)

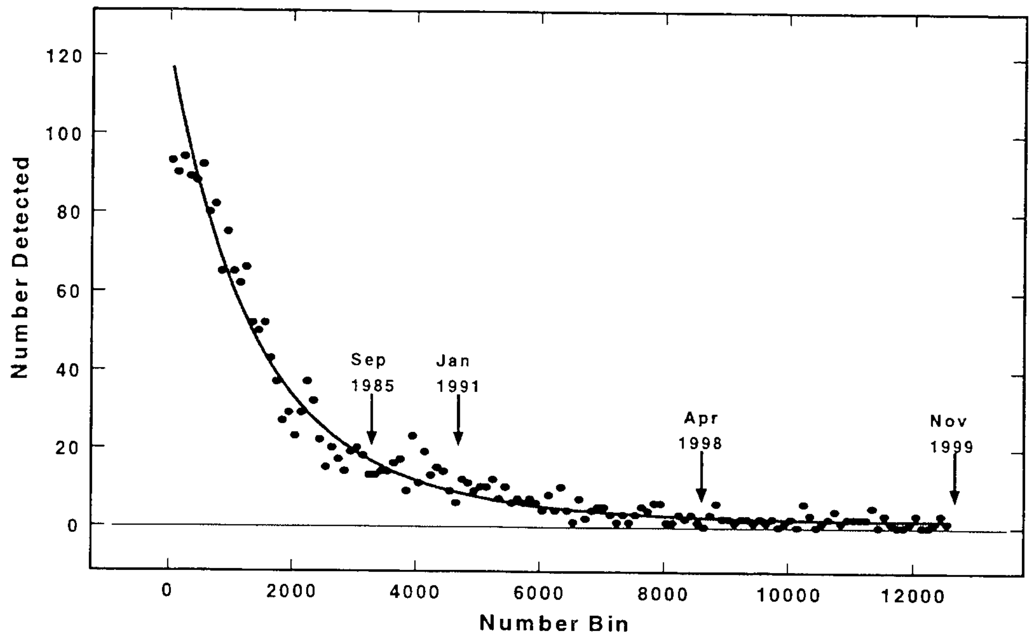


Figure 9. IRAS associations per numbered asteroid centuries. Dates of the element sets used in previous runs of IRAS asteroid association codes are indicated.

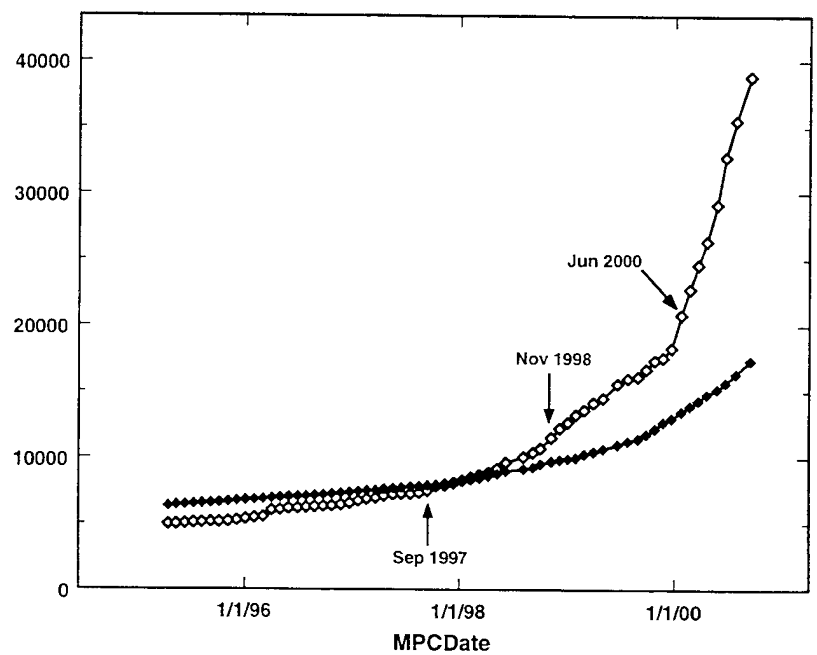


Figure 10. Sizes of known asteroid (solid diamonds) and multi-opposition asteroid (open diamonds) orbital element sets.

Albedo and diameter histograms for the new SIMPS asteroids are given in Figs 11 and 12. Although the vast majority of the higher numbered asteroids being associated have diameters between 10 and 30 km, asteroids with diameters up to nearly 100 km are still being found. Curiously, the albedo distribution is markedly different from that for small

IMPS asteroids (D < 44 km, *cf.*, Tedesco, 1994, Fig 6) where there are roughly equal numbers with albedos between 0.05 and 0.2 and dropping off sharply outside this range. The reason for this is unknown at this time but could be that the IR flux for lower albedo asteroids, although <10% higher than that for moderate albedo asteroids, may be enough to cause the latter to drop below the IRAS detection threshold.

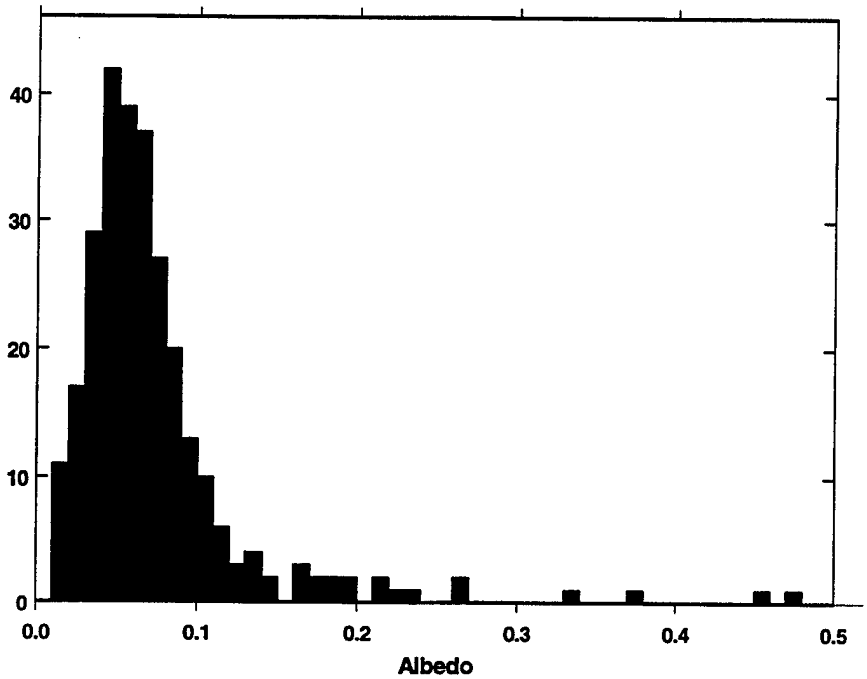


Figure 11. Albedo histogram for new SIMPS asteroids.

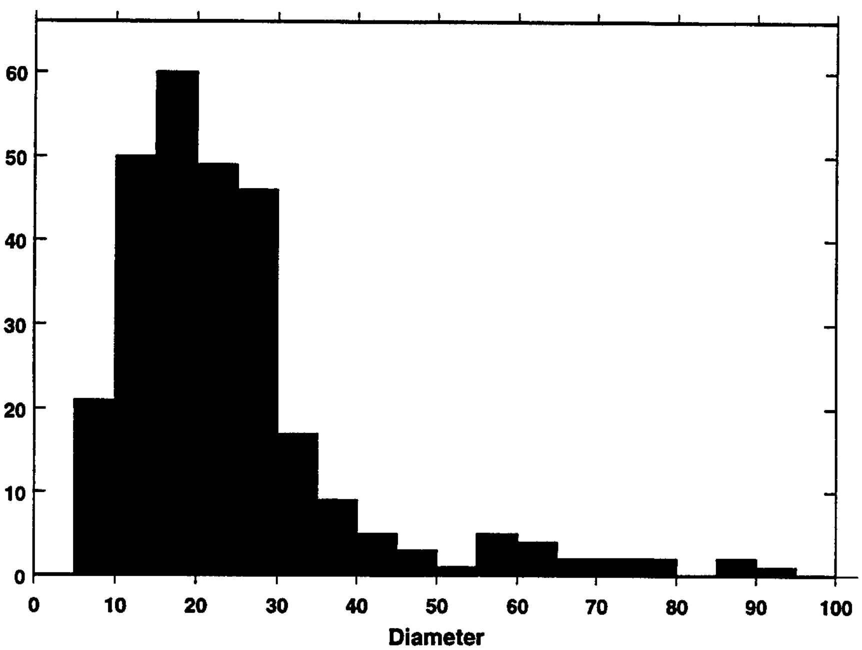


Figure 12. Diameter (km) histogram for new SIMPS asteroids.

3 THE ASTEROID STATISTICAL MODEL (ASM)

This version of the Asteroid Statistical Model includes the Main Belt family and background populations. Not included, except for their presence among the numbered asteroids, are the Near-Earth Asteroid, Jupiter Trojan, or Outer Solar System populations.

The auxiliary file (Asteroid.txt) used with the numbered asteroids in CBSD was updated (and renamed Asteroid.dat) to include the albedos and diameters from SIMPS. In addition, an albedo and diameter was added for every numbered asteroid as well as the taxonomic class and B-V color for those for which such data exist. See §3.1 for details.

The Asteroid Statistical Model consists of three modules: 1) the numbered asteroid population also referred to herein as the "real" asteroids, 2) the background (non-family) statistical model, and 3) the asteroid family statistical model. The creation of each is described below.

3.1 The Numbered ("Real") Asteroid Population

The real asteroid population is believed to be essentially complete, *i.e.,* virtually all have been discovered and numbered, for visual opposition magnitudes less than ~15.5 ± 0.25. This value is derived from Jedicke and Metcalfe (1998) by converting the completeness limiting absolute magnitudes for the three regions into which they divided the asteroid belt[2] to mean opposition magnitudes[3]. In terms of diameters, this corresponds to a diameter as small as 3 km for a high albedo asteroid in the Hungaria group (Zone 1) to as large as 103 km for a low albedo Jupiter Trojan (Zone 8). Table 1 gives the absolute visual magnitude (H), mean semi-major axis (<a>), and completeness diameter for each Zone (*cf.*, Table 3) and Albedo Class (*cf.*, Table 4) used in this study.

Table 1. Completeness Diameter (km) as a Function of Zone and Albedo Class.

Zone	H	<a>	Low	Int	Mod	High
1	14.06	1.98	9.16	6.48	4.58	3.05
2	13.12	2.30	14.19	9.98	7.06	4.71
3	12.28	2.66	20.85	14.74	10.42	6.95
4	11.81	2.89	25.79	18.23	12.90	8.60
5	11.38	3.13	31.48	22.35	15.74	10.49
4+5	11.50	3.06	29.76	21.05	14.88	9.92
6	10.75	3.53	42.17	29.82	21.09	14.06
7	9.94	4.13	61.04	43.16	30.52	20.35
8	8.80	5.20	103.13	72.92	51.56	34.38

[2] <a>, H: 2.30, 12.75; 2.80, 12.25; 3.25, 11.25

[3] <a>, Va0: 2.30, 15.13; 2.80, 15.76; 3.25, 15.57

For limiting visual magnitudes ≤ 15.5 the real asteroid module is the only asteroid model required. When the required limiting magnitude is fainter than this the number of asteroids appearing in a given search area is less than the number which would actually be observed due to the incompleteness of the numbered population: Thus the need for a "statistical" asteroid model.

Currently CBAMP uses albedos and diameters Paul Noah obtained from Mark Sykes in the early 1990s. Sykes' "model" assigns a default albedo and diameter to asteroids lacking such based upon the asteroid's semimajor axis. The assignment is based upon results for the distribution of the taxonomic classes published by Gradie and Tedesco (1982). However, the Gradie and Tedesco result was based upon a bias-correction that applied only to asteroids with diameters greater than about 50 km.

This procedure was improved by adding measured albedos from the newly created SIMPS (which at the time the Asteroid Statistical Model was created used 8,603 numbered asteroids) and from diameters and albedos based upon unpublished Tedesco and Gradie IRTF data. Next, various kinds of estimated albedos were incorporated. These come from mean albedos for the major asteroid families, a taxonomic class, and, if none of these were available, then from a B-V color.

The final step was to compute mean albedos for asteroids with measured or estimated values as functions of diameter and orbital semimajor axis. These results were then applied to asteroids for which only an absolute magnitude and semimajor axis are available. The procedure used was identical to that described in §3.2 except that for the numbered asteroids H, rather than diameter is known and so the assigned albedo and H were used to compute the adopted diameter. (For the statistical asteroids the diameter is "known", from the models that generated the orbital distributions, and so the assigned albedo and diameter were used to compute the adopted H.)

Table 2 summarizes the data available from these various sources. The code refers to that placed into the revised physical data table (Asteroid.dat) used by CBAMP and is used to identify the source of the diameter and albedo.

Table 2. Data Used in Assigning Albedos & Diameters to Numbered Asteroids.

Data Source	No. Asteroids	Code
SIMPS	2,006	1
IRTF (Tedesco-Gradie)	349	2
Family Membership	1,877	3
Taxonomic Class	959	8
B-V Color index	1,017	9
Semimajor Axis	8,603	0

3.2 The Background (Non-Family) Statistical Model

Two models are required to estimate the number of asteroids below the completeness level. This is because the size-frequency distribution varies with location in the asteroid belt and is a combination of different groups of asteroids, some of which are members of dynamical asteroid families and some not, each with their own size distribution.

The minimum set of asteroid size distributions required to realistically model the asteroids is 18: one for each of the 15 major Hirayama dynamical families, as defined by Cellino *et al.* (1991) and Zappalà *et al.* (1996), plus 3 for the "background" population. This section describes the creation of the background population model.

Because asteroid size distributions are know to vary with location within the asteroid belt, the first task was to divide the belt into physically meaningful zones. This was done by examining the distribution of asteroid semi-major axes (*cf.*, Fig. 13). The semi-major axes, rather than the proper semi-major axis, was used as the zone-defining parameter in order to include every numbered non-family asteroid since proper semi-major axes can only be computed for a sub-set of asteroid orbits. This procedure, when applied with a resolution of 0.01[4] AU, resulted in the natural division of the belt into eight zones as detailed in Table 3.

Table 3. Definition of Semi-Major Axis Zones.

Zone	a ≥	a <	e	Remark
0	0.00	2.10	> 0.18	Mars-crossers
1	1.85	2.10	≤ 0.18	Hungarias
2	2.10	2.50		
3	2.50	2.82		
4	2.82	2.95		
5	2.95	3.30		
6	3.30	3.75		Cybeles
7	3.75	4.50		Hildas
8	4.50			Trojans

Because, with the exception of zones 0 and 1, the semi-major axis was the only parameter used to define the zones, several classes of "unusual" asteroids are, incorrectly, contained within these zones. These include Near-Earth asteroids with semi-major axes ≥ 2.10 AU, possible miss-assignments of Cybeles, Hildas, and Trojans, and inclusion in the Trojan zone of all asteroids with semi-major axes ≥ 4.50 AU. For the present purpose, this "contamination" is irrelevant. The zones were used to estimate representative albedos for each of these zones and, for the main-belt (zones 2 through 5), size distributions. The number of contaminating asteroids in each of these zones is no more than 1 to 2%

[4] The difference between semi-major axis and proper semi-major axis, in those cases where they can be computed, is generally << 0.01 AU.

Following Tedesco *et al.* (1989) the albedos were parameterized as in Table 4.

Table 4. Definition of Albedo (p_H) Classes.

Albedo Class	$p_H >$	$p_H \leq$	Log. Mean p_H
Low		0.089	0.05
Intermediate	0.089	0.112	0.10
Moderate	0.112	0.355	0.20
High	0.355		0.45

The Logarithmic Mean albedo values were checked against the mean and median values of the non-family asteroid sample with radiometrically-derived albedos and were found to agree. The means (medians) are: 0.0547 (0.0533), 0.0990 (0.0986), 0.1974 (0.1883), and 0.4624 (0.4364).

Fig. 14 and Fig. 15 present albedo histograms for the numbered non-family asteroids in each of the eight zones. For each zone the top figure shows the distribution for all asteroids with albedos obtained from radiometric observations and the middle and lower figures the distributions for those asteroids with diameters ≥ 40 km and < 40 km, respectively.

These data were used to compute the bias-corrected albedo distributions using the method described by Zellner (1979) and Tedesco (1979). See Appendix 4 - Bias Correction for the details.

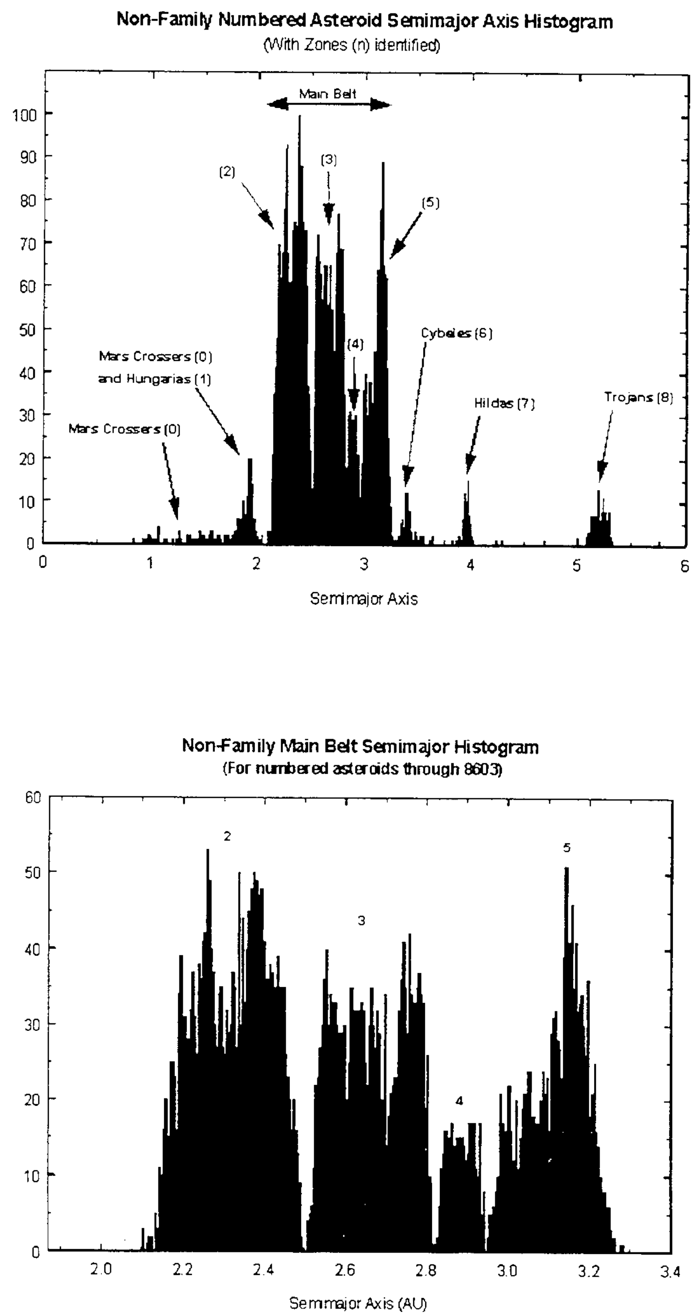


Fig. 13. Semi-major axis histograms for numbered non-family asteroids. The histogram resolution is 0.01 AU.

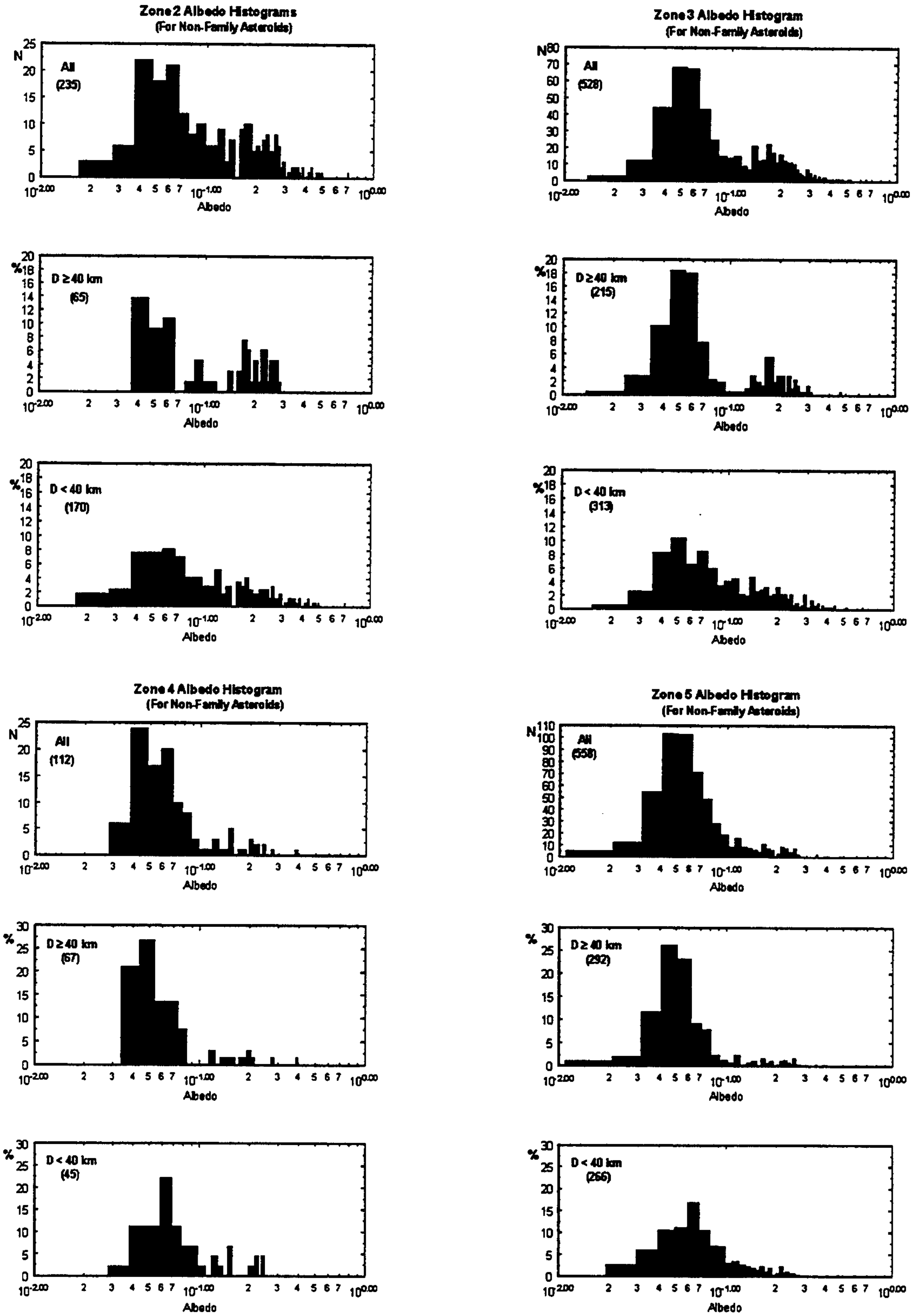


Fig. 14. Albedo histograms for numbered non-family main belt asteroids, *i.e.*, Zones 2 – 5.

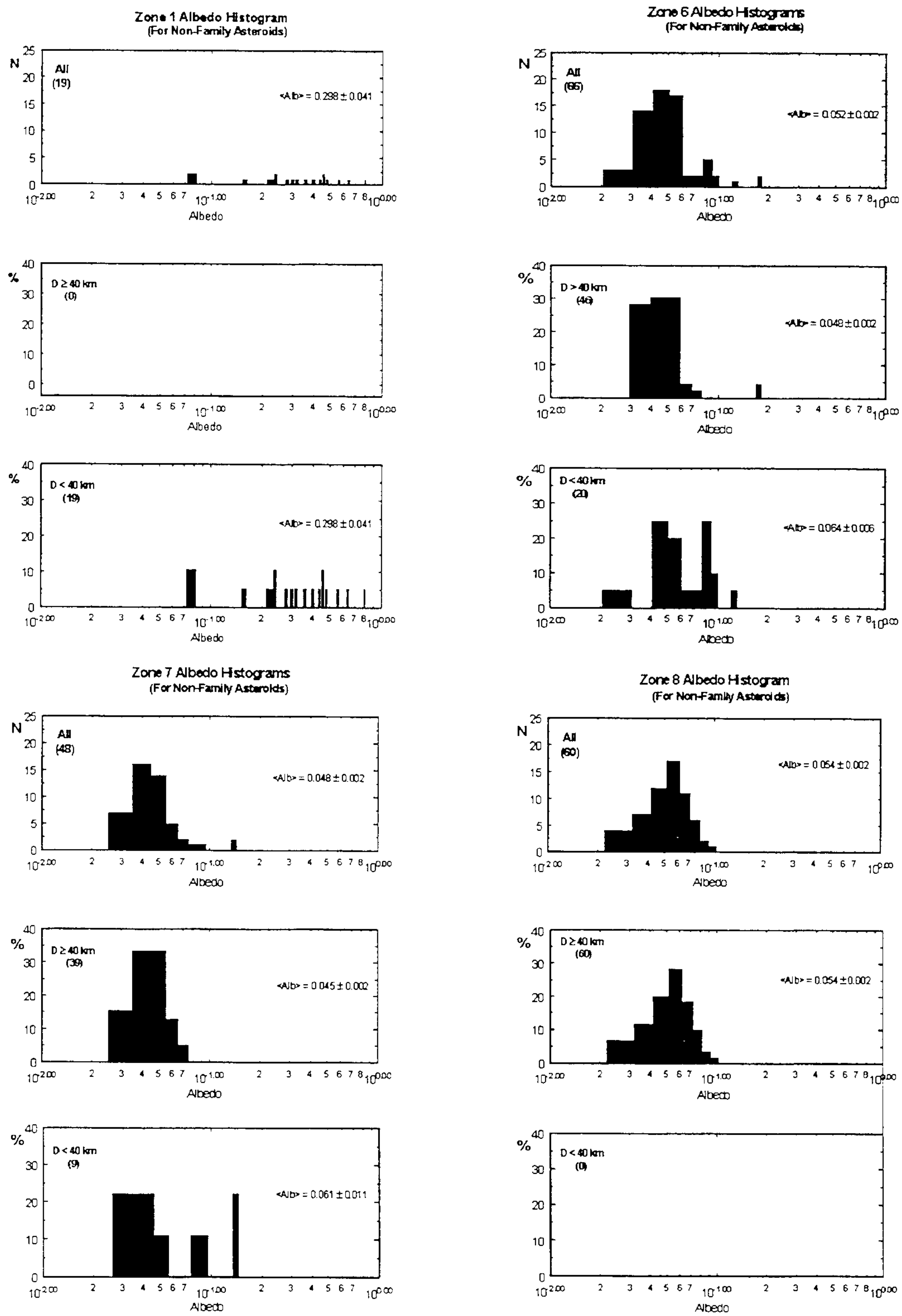


Fig. 15. Albedo histograms for numbered non-family outlier asteroids, *i.e.*, Zones 1, 6, 7, and 8.

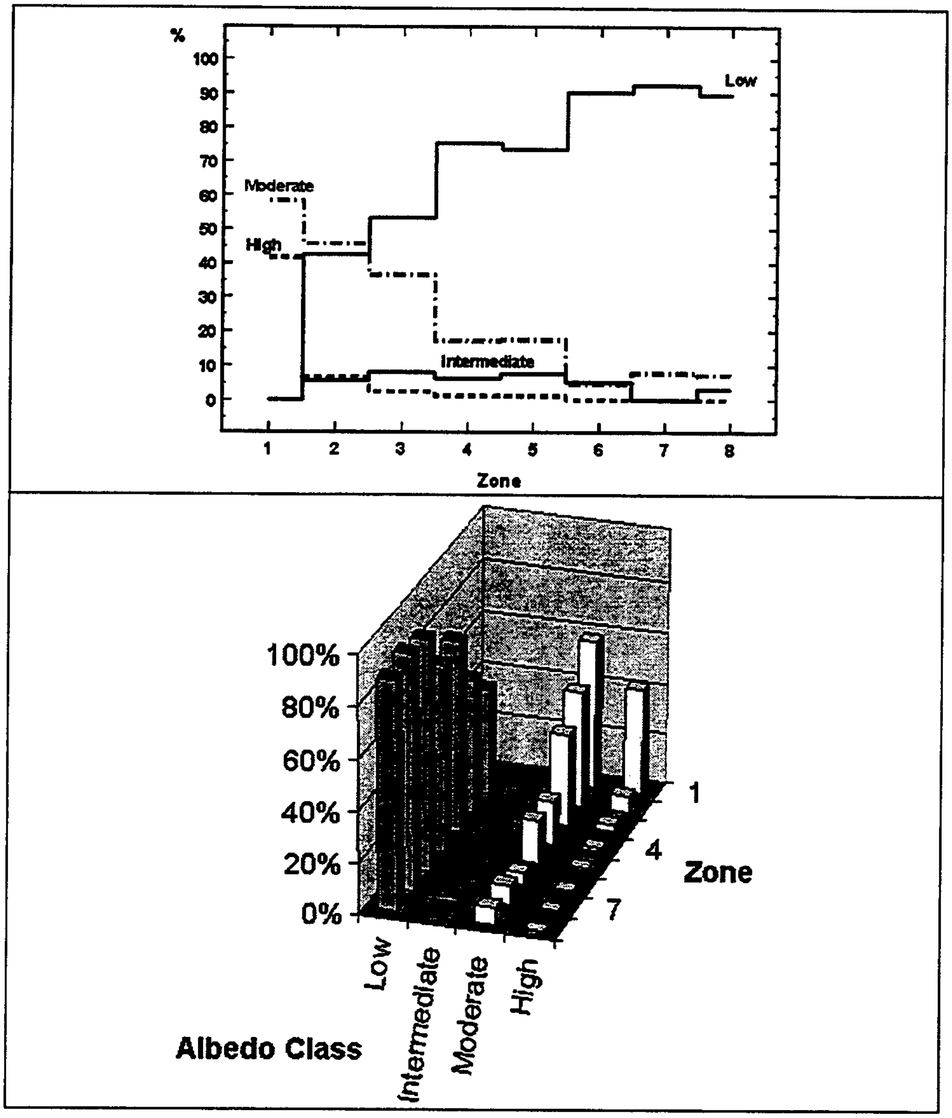


Fig. 16. Bias-Corrected albedo distributions for non-family asteroids. The same data are displayed in 2-D (top) and 3-D (bottom) views.

Fig. 16 shows the zone-normalized bias-corrected albedo distributions for the non-family asteroids. From this figure it is apparent that: 1) Zone 1 (the Hungaria region) is the only zone in which the low-albedo class asteroids are not a significant portion of the population. 2) The distributions for zones 6, 7, and 8 are essentially the same. 3) Within the main belt (zones 2, 3, 4, and 5) the albedo distribution in zones 4 and 5 is essentially identical. 4) There exists a monotonic increase in the low-to-moderate albedo ratio from zone 2 outward while the fraction of high albedo classes decreases monotonically from a maximum of 7% in zone 2 to 1% in zones 4 and 5 and zero beyond. Over these same zones, the proportion of the intermediate albedo class remains essentially constant at around a value of 6 ± 2%.

Based upon the above analysis it was decided to assign albedos to asteroids lacking such values as follows. Because the purpose of having albedos and diameters for all asteroids is to model their appearance on the sky as realistically as possible, assigning a single albedo to asteroids in each semi-major axis zone will not suffice. For example, in zone 2 (which contains 41% of the numbered main-belt asteroids) the bias-corrected fraction of low and moderate albedo asteroids is about equal (42% vs. 46%). If a single adopted albedo were used in this zone the resultant scene would be mono-modal rather than, as known from the bias analysis, strongly bi-modal. Thus, it was decided to group zones as described in the preceding paragraph, treat each separately, and assign albedos proportionately.

With the exception of zone 3, and to a lesser extent zone 2, the albedo distributions for asteroids with diameters greater than 40 km and those smaller than this display no significant differences (*cf.*, Fig. 14 and Fig. 15). For zone 2 the sample is too small to enable us to say anything definitive. There are only 65 asteroids in zone 2 with $D \geq 40$ km and no more will be found as this is well above the completeness limit. For zone 3 the statistics are better; there are 215 asteroids in this zone with $D \geq 40$ km and over 300 smaller asteroids with radiometrically-derived albedos. The albedo distribution for the larger asteroids in this zone is strongly bi-modal while that for the smaller asteroids is not. However, many of these smaller asteroids are below the completeness limit for this zone (~ 21 km for low-albedo asteroids and 11 km for moderate albedo asteroids). Thus, it is likely that the proportion of higher-albedo asteroids for zone 3 in the $D < 40$ km sample plotted in Fig. 14 is greater than in reality. For these reasons, it was decided to make no distinction between large and small asteroids. If this difference in the albedo distribution is real, then ignoring it underestimates the number of small low-albedo asteroids in this zone.

The albedos corresponding to each of the albedo classes are the logarithmic means (-1.3, -1.0, -0.7, and -0.3) of each of the class ranges rounded to 0.05. This yields 0.05 for low, 0.10 for intermediate, 0.20 for moderate, and 0.45 for the high albedo classes.

Table 5. Complete/Bias-Corrected Zonal Albedo Distribution (%).

Zone	Low	Intermediate	Moderate	High
0[1]	50	0	50	0
1	25	0	50	25
2	35/42	6/5	52/46	7/7
3	49/53	5/8	43/37	3/2
4+5	72/74	6/7	20/18	2/1
6+7+8	91/91	3/3	6/6	0/0

[1]0 = Mars-crossers with semi-major-axes in the Hungaria (Zone 1) range

There are 5,987 non-family asteroids among the first 8,603 numbered asteroids. Of these, 1,637 have radiometric albedos (1,582 from SIMPS and 55 from Tedesco and Gradie's IRTF survey). An additional 144 have albedo estimates based on a taxonomic class (91) or a B-V color (53). Only those with radiometric albedos were used to perform the bias-correction. The remaining 4,206 have no albedo information.

Table 6 summarizes the albedo data in terms of its sources as a function of zone.

Because the albedos derived from taxonomic classes and B-V are based upon measurements, albeit indirect ones, they were not replaced by zone-based albedos. The procedure for assigning a zone-based albedo is as follows. The semi-major axis and eccentricity for each non-family asteroid lacking an albedo and diameter were used to assign it to one of the six zone groups in Table 6.

Table 6. Albedo Data as a Function of Zone and Source.

Zone	SIMPS	IRTF	Taxon	B-V	None	Total
0	3	6	8	6	76	**99**
1	11	10	6	5	110	**142**
2	223	12	37	21	1935	**2,228**
3	519	9	26	13	1098	**1,665**
4+5	662	8	11	7	852	**1,540**
6+7+8	164	10	3	1	135	**313**
Totals:	**1,582**	**55**	**91**	**53**	**4,206**	**5,987**

The procedure for assigning an albedo to asteroids belonging to Zones 0 and 1 differed from that for the other zones. These two zones contain relatively few asteroids and, especially in the case of the Mars-crossers, are subject to different selection effects than the remainder of the sample. In addition, due to the simplistic way in which the zones are defined, there are a couple of hundred Mars-crossers contained in the other zones. The 50% low, 50% moderate albedo distribution for the Mars-crossers is nothing more than an educated guess but one that is consistent with that generally assumed for the Near-Earth asteroids.

For zones 2 through 8 the bias-corrected proportions of albedo classes was maintained for asteroids with diameters above the completeness limit. For asteroids with diameters below the completeness limit, the observed proportions were maintained since, due to the discovery bias, this sample should contain a disproportionate number of the higher albedo classes. The combined real and statistical models were constrained to reflect the bias-corrected proportions of albedo classes. The resultant albedo assignment algorithm using this procedure is given in Table 7.

Table 7. Numbered Asteroid Albedo Assignment Algorithm.

Zone	Algorithm (% Low; %Intermediate; %Moderate; %High)
0	0.10 for all values of Va0
1	0.29 for all values of Va0
2	35; 6; 52; 7 if Va0 ≥ 15.75 42; 5; 46; 7 if Va0 < 15.75
3	49; 5; 43; 3 if Va0 ≥ 15.75 53; 8; 37; 2 if Va0 < 15.75
4+5	72; 6; 20; 2 if Va0 ≥ 15.75 74; 7; 18; 1 if Va0 < 15.75
6+7+8	91; 3; 6; 0 if Va0 ≥ 15.75 91; 3; 6; 0 if Va0 < 15.75

There are 1,426 non-family asteroids with Va0 < 15.75 which have a radiometric-based albedo.

Table 8 gives the mean and standard deviation of this sample for each of the four albedo groups. The albedos generated for the background non-family statistical and numbered asteroid data sets are constrained to have these same mean values and standard deviations.

Table 9 presents the statistical distribution obtained by applying this procedure.

This approach was followed so that the albedo distribution of the modeled asteroids would match, on a zone-by-zone basis, the observed and bias-corrected albedo distributions. This makes for a much more realistic simulation than one in which a single mean albedo is used for all the asteroids in a given zone.

Table 8. Mean Albedos and Standard Deviations of Observed Asteroids with Va0 < 15.75.

Albedo Group	No. with Rad. Obs.	Mean Albedo	Standard Deviation
Low	848	0.0559	0.0142
Intermediate	83	0.0992	0.0068
Moderate	458	0.1977	0.0567
High	37	0.4632	0.1035

Table 9. Statistical Albedo Assignments for Numbered Non-Family Asteroids

Sample for Asteroids Numbered Through 8603

Zone	Total	No. with non-Rad Albedos	% with non-Rad Albedos	No. without an Albedo	No. with Va0 < 15.75	No. with Va0 > 15.74
2	2228	58	2.6%	1935	667	1268
3	1665	39	2.3%	1098	387	711
4+5	1540	18	1.2%	852	214	638
6+7+8	313	4	1.3%	135	11	124

Bias-Corrected (for Va0<15.75) and Observed Distributions for Above Sample

Zone	% for Va0 < 15.75				% for Va0 > 15.74			
	Low	Int	Mod	High	Low	Int	Mod	High
2	42	5	46	7	35	6	52	7
3	53	8	37	2	49	5	43	3
4+5	74	7	18	1	72	6	20	2
6+7+8	91	3	6	0	91	3	6	0

Statistical Distribution Based Upon Values Above

Zone	Nos. for Va0 < 15.75				Nos. for Va0 > 15.74			
	Low	Int	Mod	High	Low	Int	Mod	High
2	280	33	307	47	444	76	659	89
3	205	31	143	8	348	36	306	21
4+5	158	15	39	2	459	38	128	13
6+7+8	10	0	1	0	113	4	7	0

The observed albedo distribution is used for the numbered asteroids below the completeness limit (*i.e.*, those with Va0 ≥ 15.75) because this is what is actually observed for this sample. The statistical background population will use the bias-corrected distribution because it is intended to be "complete" to a limiting diameter (and not a Va0).

Table 10 summarizes the albedo distribution resulting from the procedure described above.

Table 10. Statistical Albedo Assignments for the Statistical Background Model.

Zone	Total No.	Low	Int	Mod	High
2	37,822	15,885	1,891	17,398	2,648
3	38,362	20,332	3,069	14,194	767
4+5	68,486	50,680	4,794	12,327	685

3.3 The Asteroid Family Statistical Model

It has long been recognized that the size-frequency distribution for at least some family asteroids differs from that for non-family asteroids (Tedesco, 1979; Cellino *et al.*, 1991). This fact has recently been attributed to compositional differences between family and background asteroids. To wit, "Asteroid families with material properties that differ from that of the average background population may evolve a size distribution with a different equilibrium slope than that of the background." (Durda and Dermott, 1997).

The group at the Torino observatory and their collaborators has published a series of papers during the mid-1990's in which they have modeled the disruptions which formed the major asteroid families (*e.g.,* Marzari *et al.*, 1996; Zappalà *et al.*, 1996, 1997, and Di Martino *et al.*, 1997). The results of these studies have been used to derive size-frequency distributions for each of the 15 families identified as being the major contributors to the asteroid population.

The family module combines the results of extrapolating the size distribution models for each of the 15 families into a single file containing ~1.7×10^6 statistical asteroids with diameters greater than 1 km. The "background" population is herein defined to be all those asteroids not belonging to one of the 15 major Hirayama dynamical families.

The 15 families, with the modeled parent body diameter in km in parentheses, are: Adeona (189), Dora (88), Eos (218), Erigone (91), Eunomia (284), Flora (164), Gefion (74), Hygiea (481), Koronis (119), Maria (130), Massalia (151), Merxia (42), Themis (369), Veritas (167), and Vesta (500).

The Adeona family will be used as an example of how the 15 family models were created. (See Appendix 5 – Creation of the Asteroid Family Statistical Models for additional details.) The Adeona file was produced using a list of diameters, created by a program provided by Dr. Alberto Cellino of the Torino Observatory, that models the size distribution for any given family. The number of model diameters is such to ensure completeness down to 1 km. Then, using the location of the family barycenter and the overall behavior of the size-velocity relationship for the same family, the velocity vectors to be applied to each object, having a given diameter, are computed and the velocity converted into osculating (a, e, i) elements. The angular elements (Ω, ω, and M_0) are taken at random. This is done for all model diameters below the completeness diameter. Above the completeness diameter real family members are used.

This procedure produced 100,000 objects with diameters greater than 1 km resulting from the collisional event that created the Adeona family. The final number of objects surviving, *i.e.*, not eliminated because they were immediately ejected from the main belt ($2.1 > a > 3.3$) or because they became Mars- or Jupiter-crossers (the latter possibility, although included for the sake of completeness, is not realistic, but the first one is frequent in the inner belt) depends on the seed used for the simulation's random number generator but is very weakly dependent on it. Using the modeled velocity distribution led to 99,983 surviving members. The orbital element distribution of this sample (each of which has a model diameter) was constrained to match the distribution of the known family members.

There are 13 Adeona members with known albedos (*cf.*, Fig. 17.). The mean and standard deviation of these 13 objects is assumed to be representative of the entire family. Thus, albedos were randomly assigned to each of the 99,983 model asteroids such that the mean and standard deviation for this sample matched that of the 13 objects with measured albedos. This is not as crazy as it seems at first glance because it happens that the albedo distributions for members of all 15 families being considered here are rather narrowly distributed. (With the exception of the Massalia and Merxia Families, for which only one measured albedo exists, all Families have at least five members with a measured albedo and two {Eos with 104 and Themis with 134}, have over 100.)

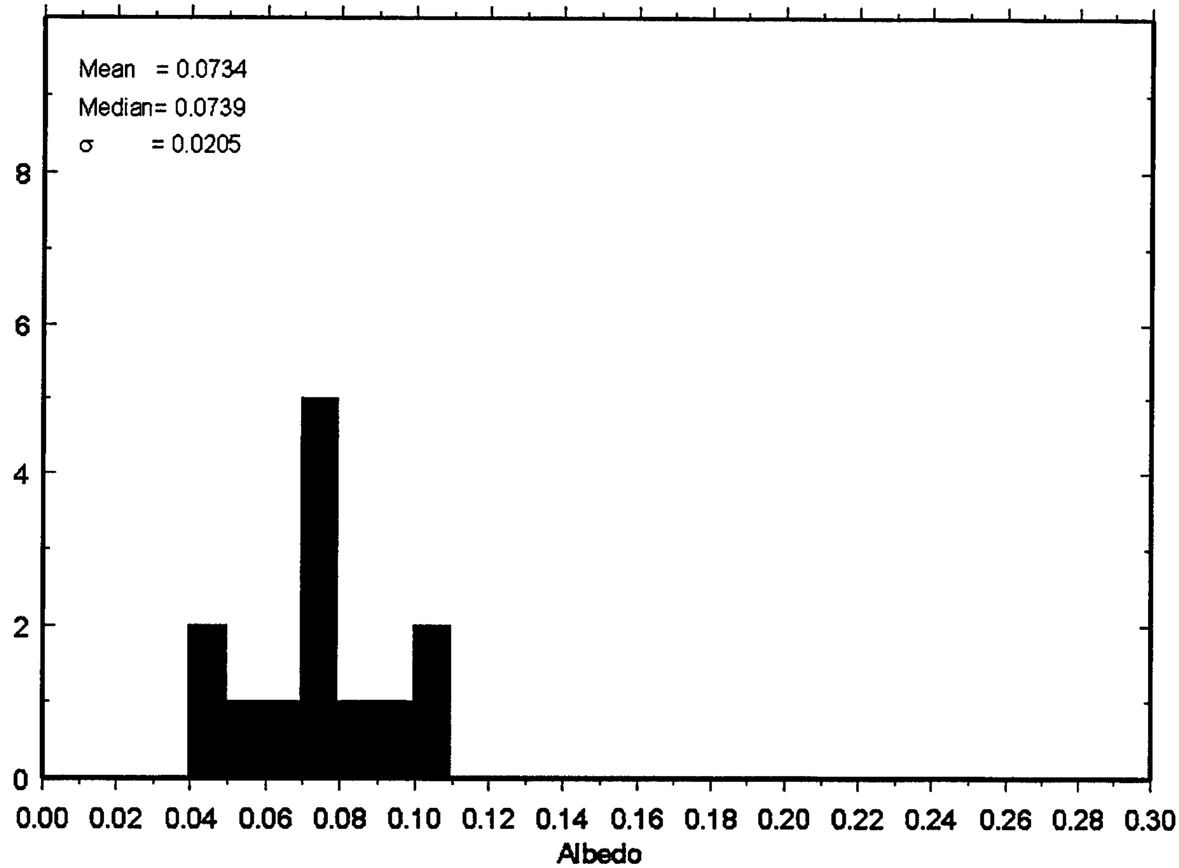


Fig. 17. Observed albedo distribution for the 13 Adeona Family members with measured albedos.

Next, the absolute visual magnitude (H) for each of the model Adeona Family members was computed from the diameter (D) and albedo (p_V): $D = 10^{\{3.1236 - 0.2 H - 0.5 \log(p_V)\}}$. All were assigned the default value of 0.15 for the slope parameter (G)[5].

[5] Less than 1% of the numbered asteroids have a measured slope parameter.

This file enables us to calculate the position and brightness (at any wavelength from the visual to the mid-IR, *i.e.*, from about 0.3 to 30 μm) for all members of the Adeona family.

The ecliptic latitude distribution for the numbered asteroids and those asteroids from the model Adeona family are shown in Fig. 18 and Fig. 19, respectively. The peaks in the ecliptic latitude distribution of the Adeona family are analogous to those observed for the Zodiacal dust bands and for which the Eos, Themis, and Koronis families are believed responsible.

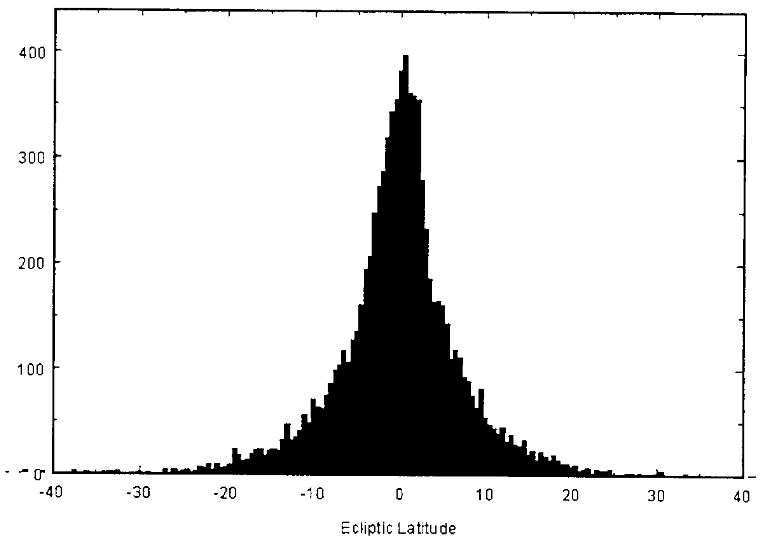


Fig. 18. Distribution of Numbered Asteroids in Ecliptic Coordinates.

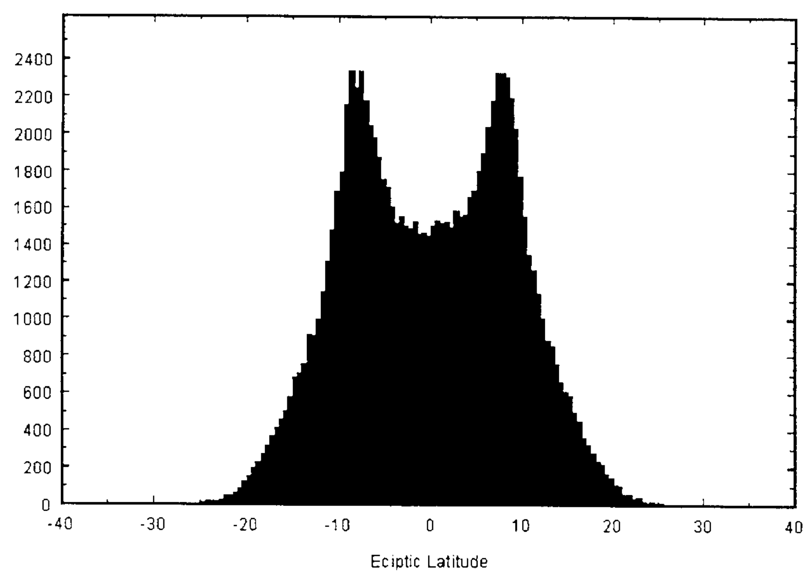


Fig. 19. Distribution of model Adeona Family Asteroids in Ecliptic Coordinates.

It appears that the ecliptic latitude distribution of small asteroids may differ markedly from that of the larger asteroids. In fact, it is beginning to look like the peak in the sky density of asteroids larger than 1 km in diameter is not centered on the ecliptic.

Fig. 20 gives the distribution of the observed V magnitudes for the numbered asteroids and Fig. 21 those asteroids from the modeled Adeona family. Note that the vast majority of the modeled Adeona family asteroids have V > 22 whereas only a small fraction of 1% of the numbered asteroids are this faint. This too is expected given that, as shown in Fig. 22, the vast majority of the modeled family members have diameters less than 2 km whereas only a handful of main-belt asteroids this small have yet been numbered. Note that the fall-off in the V magnitude distribution for the numbered asteroids is due to discovery incompleteness whereas that for the modeled Adeona Family is due to the truncation of the size-frequency extrapolation at 1 km.

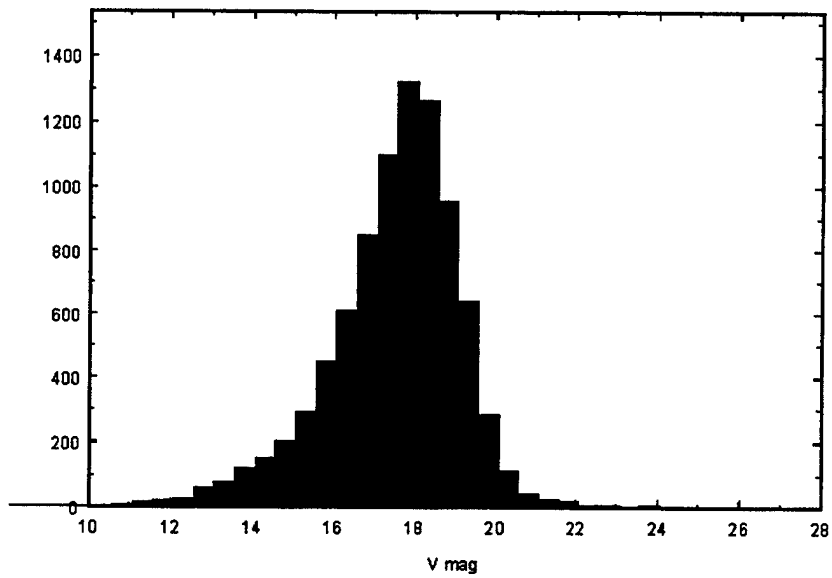


Fig. 20. Apparent V magnitude histogram for the numbered asteroids.

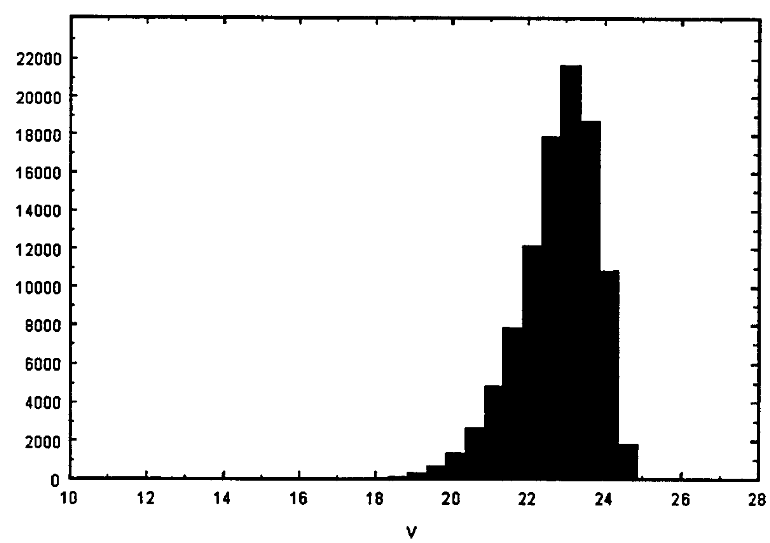


Fig. 21. Apparent V magnitude histogram for the model Adeona Family.

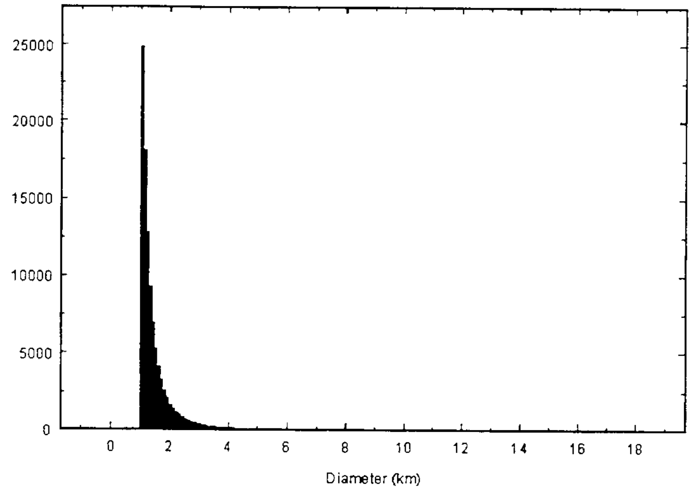


Fig. 22. Diameter histogram for the model Adeona Family.

3.4 The Asteroid Statistical Model Database

The family membership list for the numbered asteroids was used to update the file of physical data (ASTEROID.DAT) used by the CBSD asteroid module (CBAMP). Every numbered asteroid through 5383, the highest numbered asteroid for which this data was available, that belongs to a major asteroid family now has a field indicating this. The diameter and albedo for the numbered family asteroids were assigned in the same fashion as those for the statistical family members (*cf.*, §3.3 The Asteroid Family Statistical Model). Those numbered asteroids not a member of one of the 15 asteroid families used here had their diameters and albedos assigned as described in Table 2.

The total number of "statistical" family members is 1,739,574. To this were added the statistical "background" model bringing the total number of asteroids in the Asteroid Statistical Model to 1,883,408. This database was provided as two files, one ASCII (ASM99_Elem.txt - 171,390,128 bytes) and one binary (ASM99_Elem.bin - 150,672,640 bytes). The format of the Asteroid Statistical Model files is given in Table 11.

Not included in this release are the Near-Earth Asteroid Population (around 2,500 statistical asteroids), the Jupiter Trojan statistical population (about 100,000 asteroids), and the Trans-Neptunian population.

Table 11. Asteroid Statistical Model File Format.

Tq	– time of perhelion passage as a Julian Date
q	– perhelion distance in AU
e	– eccentricity
ArgPer	– argument of perhelion in degrees
AscNode	– ascending node in degrees
i	– inclination in degrees
H	– absolute V magnitude
Diam	– diameter in km
Albedo	– geometric albedo
Fam	– The family code as the first three letters, all upper case, of the name of the lowest numbered family member or the Zone(s) if a background object

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Appendix 1. SIMPS RUN STREAM

This appendix summaries the SIMPS run stream, *i.e.*, the order in which the codes must be run to achieve the desired output. See §2.2 CSIMPS for further details.

Except for akm and genak04, all codes are in C++.

The PreProcess.Bat file runs the following code:

```
genip03 /auto %1
```

The AK_Proc.Bat file runs the following sequence of codes:

```
FORTRAN →akm
FORTRAN →genak04
        bgenak09 /auto
        bgenak06 /auto
        bgenak05 /auto
        brdak05
        bgenak10 /auto
        bAdd2AK10 /auto
        bStatStat /auto
        bIMPSUt01 /auto
        bIMPSUt02 /auto
        bGenAK11 /auto
```

The AD_Proc.Bat file runs the following sequence of codes:

```
bin\LiMiss /auto
bin\ADLBH /auto
bin\genfp01
bin\Fpard /auto
bin\GenAD07 /auto
bin\genad04 /auto
```

The Create_FinalProducts.Bat file runs the following sequence of codes:

```
genfp20 /auto
genfp21 /auto
genfp102 /auto
rdak05
genfp105 /auto
genfp106 /auto
genfp108 /auto
cnt_astw /auto
cnt_pstw /auto
```

Appendix 2. SIMPS RESULTS

Below are the results for the new SIMPS asteroid associations, *i.e.*, for associations for asteroids not previously published in IMPS. The format is identical to that in IMPS (Tedesco, 1992, Chapter 12) except for omission of the AstatW field.

Asteroid	H	p_H	σp_H	D	σ_D	PLC	US	UO	FOR
4709 Ennomos	8.90	0.0744	0.009	80.85	4.3	0.10	2	3	1.00
4712 Iwaizumi	10.90	0.0933	0.007	28.75	1.0	0.10	10	22	1.00
4717 Kaneko	11.20	0.1808	0.026	17.99	1.2	0.10	4	5	1.00
4730 1980 XZ	11.10	0.1022	0.020	25.06	2.1	0.10	2	2	0.33
4732 Froeschle	11.30	0.0599	0.004	29.84	1.0	0.10	4	12	1.00
4754 Panthoos	10.10	0.0571	0.010	53.15	4.2	0.10	2	3	0.50
4759 1978 VG10	11.90	0.1255	0.022	15.64	1.2	0.10	2	3	0.50
4768 Hartley	11.30	0.0398	0.004	36.63	1.7	0.10	1	3	1.00
4772 1989 VM	11.80	0.0409	0.004	28.68	1.2	0.10	4	10	0.67
4783 Wasson	13.70	0.0455	0.011	11.34	1.1	0.10	1	2	0.20
4790 Petrpravec	11.80	0.1084	0.021	17.62	1.5	0.10	2	2	0.29
4791 Iphidamas	9.90	0.0579	0.009	57.85	4.0	0.10	3	3	0.75
4812 Hakuhou	14.40	0.0580	0.013	7.28	0.7	0.10	2	2	1.00
4831 1988 RX11	12.40	0.0157	0.003	35.18	3.2	0.10	1	2	0.25
4833 Meges	9.10	0.0531	0.008	87.33	5.8	0.15	6	14	1.00
4834 Thoas	9.20	0.0490	0.005	86.82	3.8	0.10	4	8	1.00
4836 Medon	9.50	0.0610	0.009	67.73	4.7	0.10	3	4	1.00
4837 1989 ME	11.60	0.0693	0.024	24.16	3.3	0.49	2	3	0.50
4840 Otaynang	11.90	0.0398	0.017	27.78	4.4	0.99	3	4	0.60
4843 Megantic	11.00	0.1039	0.013	26.02	1.5	0.10	2	4	1.00
4870 Shcherban'	11.30	0.0834	0.014	25.29	1.9	0.10	2	4	0.67
4874 Burke	12.00	0.0818	0.017	18.50	1.7	0.10	1	2	0.17
4889 Praetorius	11.90	0.0908	0.014	18.39	1.3	0.10	2	4	1.00
4907 Zoser	12.10	0.0529	0.007	21.98	1.3	0.10	3	5	0.60
4918 Rostropovich	13.20	0.0651	0.011	11.93	0.9	0.10	1	2	0.50
4930 Rephiltim	11.00	0.0720	0.010	31.27	1.9	0.76	7	17	1.00
4955 Gold	11.30	0.0599	0.012	29.84	2.7	0.10	1	2	0.14
4958 Wellnitz	11.50	0.0582	0.011	27.61	2.3	0.10	1	2	0.33
4959 Niinoama	10.80	0.1082	0.021	27.96	2.4	0.10	2	2	1.00
4966 1981 EO34	13.60	0.0687	0.013	9.66	0.8	0.10	2	2	0.40
4967 Glia	10.70	0.1054	0.016	29.67	2.0	0.10	2	4	0.50
4973 Showa	11.30	0.0865	0.023	24.84	2.7	0.10	1	2	0.33
5022 1984 HE1	11.70	0.0324	0.005	33.77	2.2	0.10	4	5	1.00
5024 1985 VP	11.50	0.0545	0.010	28.52	2.2	0.10	3	3	0.50
5025 1986 TS6	9.80	0.0635	0.012	57.83	4.9	0.10	2	2	0.40
5027 Androgeos	9.40	0.0917	0.015	57.86	4.3	0.10	3	3	0.60
5070 Arai	11.10	0.0792	0.012	28.47	1.9	0.10	3	5	1.00
5079 1975 DB	12.60	0.0592	0.008	16.50	1.0	0.10	3	5	1.00
5081 1976 WC1	12.10	0.1072	0.019	15.44	1.2	0.10	2	3	0.50
5092 Manara	11.00	0.1014	0.017	26.34	1.9	0.10	3	4	0.33
5095 Escalante	13.20	0.1203	0.021	8.78	0.7	0.10	3	3	0.38
5097 Axford	13.20	0.0547	0.010	13.02	1.1	0.10	2	3	0.50
5102 Benfranklin	12.70	0.0443	0.011	18.20	1.9	0.10	1	2	0.25
5105 Westerhout	12.60	0.0874	0.021	13.58	1.4	0.10	2	2	0.20
5130 Ilioneus	9.80	0.0602	0.013	59.40	5.4	0.10	1	2	0.33
5133 Phillipadams	11.50	0.0697	0.015	25.23	2.3	0.10	2	2	0.29

Asteroid	H	p_H	σp_H	D	σ_D	PLC	US	UO	FOR
5140 Kida	11.40	0.0683	0.013	26.70	2.2	0.10	2	2	0.29
5144 Achates	8.90	0.0576	0.007	91.91	5.1	0.10	3	5	0.75
5153 1940 GO	11.20	0.0735	0.011	28.21	1.8	0.51	4	11	0.67
5176 1989 AU	12.20	0.0849	0.007	16.56	0.7	0.10	3	9	1.00
5185 Alerossi	12.20	0.1408	0.031	12.86	1.2	0.10	2	2	0.33
5192 Yabuki	10.40	0.0966	0.008	35.57	1.3	0.10	3	7	1.00
5202 1983 XX	13.20	0.0893	0.012	10.19	0.6	0.10	2	3	0.50
5209 1989 CW1	10.10	0.0506	0.009	56.41	4.6	0.10	2	2	0.33
5222 Ioffe	11.00	0.1463	0.012	21.92	0.9	0.10	6	9	1.00
5225 Loral	12.60	0.0459	0.009	18.73	1.6	0.10	2	3	0.50
5236 Yoko	13.00	0.1383	0.039	8.98	1.0	0.10	1	2	0.09
5249 Giza	12.10	0.0517	0.022	22.23	3.6	0.88	5	8	0.50
5254 Ulysses	8.80	0.0869	0.011	78.34	4.4	0.10	6	12	1.00
5255 Johnsophie	12.10	0.0723	0.018	18.80	2.0	0.10	1	2	0.33
5259 Epeigeus	10.30	0.0739	0.018	42.59	4.4	0.10	2	2	0.29
5262 Brucegoldberg	10.90	0.0698	0.022	33.25	4.2	0.38	2	2	0.40
5264 Telephus	9.50	0.0522	0.008	73.26	5.0	0.10	2	3	0.40
5283 Pyrrhus	9.30	0.0807	0.014	64.58	5.0	0.10	3	4	0.60
5316 Filatov	11.50	0.0417	0.009	32.62	3.0	0.10	1	2	0.50
5330 Senrikyu	11.80	0.2227	0.043	12.29	1.0	0.10	2	2	0.50
5337 Aoki	11.50	0.0420	0.005	32.52	1.9	0.10	3	4	0.50
5358 1992 QH	11.50	0.2141	0.038	14.40	1.1	0.10	2	2	0.50
5374 Hokutosei	11.20	0.0606	0.022	31.06	4.5	0.96	3	6	0.75
5384 1957 VA	13.80	0.0720	0.012	8.61	0.7	0.10	2	3	0.14
5399 Awa	11.90	0.0754	0.010	20.18	1.2	0.26	2	5	1.00
5416 1978 VE5	12.20	0.0697	0.013	18.28	1.5	0.10	2	2	0.67
5420 1982 JR1	13.00	0.0731	0.009	12.35	0.7	0.10	2	6	0.33
5435 Kameoka	11.40	0.0737	0.011	25.70	1.7	0.10	1	2	1.00
5439 Couturier	11.70	0.0358	0.008	32.11	3.1	0.10	1	2	0.17
5443 Encrenaz	12.90	0.0801	0.017	12.36	1.1	0.10	2	2	0.33
5458 Aizman	11.70	0.0526	0.011	26.49	2.4	0.10	1	2	0.25
5468 Hamatonbetsu	11.70	0.0748	0.010	22.21	1.3	0.26	5	7	1.00
5484 Inoda	12.60	0.1062	0.021	12.32	1.0	0.10	1	2	0.50
5489 Oberkochen	11.50	0.3398	0.056	11.43	0.8	0.10	2	3	1.00
5495 Rumyantsev	11.10	0.0833	0.036	27.76	4.6	0.43	2	2	0.20
5521 Morpurgo	12.40	0.2393	0.041	9.00	0.7	0.10	2	2	0.25
5528 1992 AJ	10.90	0.1348	0.033	23.92	2.5	0.10	2	2	0.40
5567 1953 FK1	10.80	0.0845	0.017	31.64	2.8	0.10	2	2	1.00
5572 Bliskunov	12.00	0.0686	0.008	20.20	1.1	0.10	5	10	0.83
5576 Albanese	12.20	0.0681	0.009	18.49	1.1	0.10	3	6	0.75
5592 Oshima	11.50	0.0686	0.016	25.43	2.5	0.72	6	10	1.00
5603 Rausudake	10.50	0.0622	0.011	42.34	3.2	0.10	2	2	0.33
5616 Vogtland	13.50	0.0261	0.004	16.43	1.2	0.10	3	3	0.33
5641 McCleese	12.70	0.4552	0.088	5.68	0.5	0.10	1	2	0.07
5647 1990 TZ	11.30	0.4729	0.072	10.62	0.7	0.10	1	2	1.00
5651 Traversa	11.70	0.0511	0.004	26.88	0.9	0.10	7	17	1.00
5654 Terni	12.10	0.0684	0.006	19.32	0.8	0.10	6	16	0.75
5661 Hildebrand	10.10	0.1364	0.026	34.37	2.9	0.10	2	2	0.50
5704 Schumacher	11.80	0.0515	0.007	25.57	1.6	0.10	2	5	1.00
5709 1977 TS3	12.00	0.0831	0.018	18.36	1.7	0.10	2	2	0.67
5711 1978 SO4	11.10	0.0426	0.010	38.81	3.9	0.10	2	2	0.50
5747 1991 CO3	12.50	0.2670	0.021	8.13	0.3	0.52	5	7	0.45

Asteroid	H	p_H	σp_H	D	σ_D	PLC	US	UO	FOR
5757 Ticha	12.00	0.0632	0.007	21.05	1.1	0.10	4	8	0.67
5771 Somerville	12.40	0.0372	0.006	22.83	1.7	0.10	2	3	0.50
5832 1991 LE1	11.60	0.1146	0.021	18.80	1.5	0.54	4	10	0.67
5833 Peterson	10.70	0.0901	0.011	32.08	1.8	0.10	6	8	0.75
5849 1990 HF1	10.20	0.1823	0.035	28.39	2.4	0.10	1	2	0.50
5852 Nanette	12.30	0.0353	0.003	24.53	1.1	0.10	2	6	1.00
5870 Baltimore	12.90	0.2150	0.058	7.54	0.8	0.93	7	16	0.70
5889 Mickiewicz	11.70	0.0726	0.010	22.55	1.4	0.10	6	6	1.00
5900 Jensen	12.10	0.0287	0.006	29.81	2.7	0.10	2	2	0.40
5914 1990 WK	10.80	0.0570	0.005	38.53	1.7	0.10	4	11	1.00
5919 Patrickmartin	11.60	0.0968	0.025	20.45	2.2	0.10	1	2	0.25
5922 Shouichi	11.80	0.0542	0.006	24.93	1.3	0.10	4	6	0.67
5924 Teruo	13.00	0.0693	0.014	12.68	1.1	0.96	5	7	0.83
5957 Irina	12.00	0.1121	0.024	15.81	1.4	0.10	2	2	0.29
5959 Shaklan	11.00	0.1770	0.027	19.94	1.4	0.10	4	4	0.67
6038 1989 EQ	12.20	0.0443	0.004	22.93	0.9	0.10	6	14	0.75
6057 Robbia	11.10	0.0852	0.013	27.43	1.9	0.20	2	5	0.67
6059 1979 TA	14.50	0.0413	0.005	8.23	0.5	0.12	5	8	0.71
6090 1989 DJ	9.40	0.0553	0.011	74.53	6.2	0.94	5	9	0.83
6111 1979 SP13	12.90	0.0817	0.007	12.23	0.5	0.10	9	15	0.90
6129 Demokritos	12.30	0.0863	0.009	15.69	0.8	0.10	5	10	0.83
6137 1991 BY	11.00	0.0860	0.010	28.60	1.5	0.10	4	9	1.00
6150 Neukum	12.20	0.0987	0.022	15.36	1.5	0.10	2	2	0.25
6157 Prey	13.90	0.0171	0.005	16.86	1.9	0.10	1	2	0.17
6174 Polybius	11.90	0.0723	0.006	20.61	0.8	0.10	5	12	1.00
6187 1988 RD5	12.50	0.0616	0.006	16.94	0.7	0.10	7	11	0.70
6192 1990 KB1	12.70	0.2669	0.058	7.42	0.7	0.10	2	2	0.33
6222 1980 PB3	11.30	0.0641	0.006	28.85	1.3	0.10	7	13	0.88
6255 Kuma	12.50	0.0342	0.006	22.72	1.7	0.10	2	3	0.29
6279 1977 UO5	12.40	0.0684	0.013	16.83	1.4	0.10	1	2	1.00
6295 Schmoll	13.60	0.1114	0.024	7.59	0.7	0.10	2	2	0.50
6336 Dodo	13.50	0.0195	0.004	18.98	1.8	0.10	2	2	0.25
6340 Kathmandu	12.00	0.0702	0.014	19.97	1.7	0.10	2	2	0.40
6348 1995 CH1	13.10	0.0726	0.016	11.84	1.1	0.10	1	2	0.20
6349 Acapulco	12.00	0.0757	0.010	19.24	1.2	0.10	3	5	0.38
6350 Schluter	11.60	0.0671	0.012	24.56	2.0	0.10	2	2	1.00
6355 1969 TX5	11.30	0.0663	0.010	28.38	1.9	0.10	3	3	0.75
6359 Dubinin	11.50	0.0448	0.009	31.47	2.7	0.79	6	18	1.00
6362 1979 KO	11.20	0.0373	0.008	39.58	3.5	0.10	1	2	0.25
6372 Walker	11.10	0.0443	0.005	38.04	1.9	0.10	8	14	0.80
6392 1990 HR	11.00	0.0754	0.027	30.55	4.3	0.37	2	2	0.67
6404 Vanavara	12.90	0.0279	0.007	20.93	2.3	0.46	3	5	0.75
6453 1991 NY	13.60	0.1032	0.013	7.88	0.5	0.10	3	4	0.50
6475 Refugium	10.40	0.1136	0.031	32.80	3.7	0.59	4	6	0.80
6479 Leoconnolly	12.70	0.0507	0.006	17.02	1.0	0.10	2	5	0.33
6570 Tomohiro	12.10	0.0546	0.007	21.62	1.3	0.10	4	5	0.33
6606 Makino	12.40	0.0287	0.004	26.00	1.8	0.10	2	3	0.22
6613 1994 LK	12.30	0.0430	0.007	22.24	1.6	0.20	6	11	1.00
6619 1973 SS4	10.70	0.1266	0.021	27.07	2.0	0.10	3	3	0.50
6621 Timchuk	13.50	0.0512	0.005	11.72	0.5	0.15	4	10	0.50
6631 Pyatnitskij	13.10	0.0494	0.008	14.35	1.0	0.10	2	4	0.67
6648 1991 PM11	13.00	0.1937	0.038	7.59	0.6	0.10	2	2	0.22

Asteroid	H	p_H	σp_H	D	σ_D	PLC	US	UO	FOR
6687 Lahulla	14.30	0.0192	0.010	13.25	2.5	0.55	2	2	0.29
6785 1990 VA7	11.10	0.0849	0.015	27.50	2.2	0.10	1	2	0.33
6794 1992 DK	11.00	0.0978	0.020	26.82	2.4	1.00	6	7	1.00
6862 Virgiliomarcon	11.40	0.0624	0.008	27.92	1.5	0.10	2	5	1.00
6868 1992 HD	13.00	0.0493	0.008	15.04	1.1	0.10	2	3	0.33
6879 Hyogo	12.20	0.0535	0.006	20.87	1.0	0.10	4	8	0.67
6895 1987 DG6	13.50	0.0273	0.007	16.06	1.7	0.10	1	2	0.17
6925 Susumu	12.30	0.0481	0.005	21.02	1.1	0.15	6	13	1.00
6939 Lestone	13.70	0.0212	0.004	16.62	1.5	0.10	1	2	0.20
6974 1992 MC	11.80	0.1381	0.029	15.61	1.4	0.10	2	2	0.25
6984 Lewiscarroll	10.80	0.0425	0.008	44.60	3.6	0.10	2	3	0.50
6989 1994 XH1	11.40	0.1725	0.045	16.80	1.8	0.10	1	2	0.14
7019 1992 EM1	13.20	0.0889	0.014	10.22	0.7	0.10	4	4	0.67
7050 1982 FE3	13.00	0.0390	0.005	16.90	1.0	0.10	2	4	0.50
7052 1988 VQ2	12.40	0.1682	0.029	10.73	0.8	0.10	1	2	0.17
7083 Kant	12.50	0.1161	0.022	12.34	1.0	0.10	3	3	0.60
7096 Napier	15.30	0.0428	0.007	5.59	0.4	0.10	2	3	0.67
7119 Hiera	9.80	0.0364	0.008	76.40	7.0	0.10	2	2	0.50
7170 1987 MK	13.30	0.0998	0.027	9.21	1.0	0.19	2	2	0.33
7200 1994 NO	14.00	0.0346	0.005	11.32	0.8	0.10	3	4	0.60
7217 Dacke	11.50	0.0511	0.009	29.47	2.4	0.10	2	2	1.00
7331 Balindblad	11.50	0.0740	0.016	24.49	2.3	0.10	2	2	0.29
7366 1996 UY	11.60	0.0311	0.006	36.07	3.2	0.10	1	2	0.06
7394 1985 QX4	11.10	0.0326	0.005	44.33	3.3	0.10	2	3	0.18
7466 1989 VC2	12.00	0.0552	0.010	22.53	1.8	0.10	2	2	0.33
7505 1997 AM2	11.90	0.3732	0.066	9.07	0.7	0.10	1	2	0.33
7536 Fahrenheit	11.80	0.0549	0.011	24.77	2.2	0.10	1	2	0.20
7588 1992 FJ1	11.20	0.0429	0.004	36.91	1.7	0.10	6	14	0.86
7605 1995 SR1	11.60	0.0426	0.005	30.84	1.8	0.19	6	15	1.00
7611 1996 BW1	11.80	0.0653	0.010	22.71	1.5	0.10	2	3	1.00
7612 1996 CN2	11.50	0.0896	0.020	22.25	2.1	0.10	2	3	1.00
7635 1983 VH1	11.40	0.0924	0.009	22.94	1.0	0.10	5	11	0.56
7641 1986 TT6	9.30	0.0708	0.007	68.97	3.2	0.10	4	7	0.80
7711 Rip	12.90	0.0489	0.009	15.81	1.3	0.10	3	4	0.50
7730 1978 NN1	13.50	0.0281	0.003	15.83	0.9	0.10	2	4	0.50
7750 McEwen	12.60	0.1036	0.020	12.47	1.1	1.00	5	9	0.83
7796 Jaracimrman	13.60	0.0408	0.006	12.54	0.9	0.10	3	4	0.50
7812 Billward	13.30	0.0153	0.004	23.48	2.6	0.10	1	2	0.17
7859 1979 US	13.30	0.0330	0.008	16.00	1.7	0.10	2	2	0.22
7868 Barker	12.80	0.0395	0.007	18.43	1.4	0.10	3	4	0.50
7874 1991 BE	12.50	0.0946	0.009	13.66	0.6	0.10	6	10	0.75
7880 1992 OM7	12.80	0.0430	0.008	17.66	1.5	0.10	2	2	0.25
7895 Kaseda	10.90	0.0949	0.011	28.51	1.6	0.24	6	14	1.00
7949 1992 SU	12.40	0.0569	0.011	18.45	1.6	0.96	8	21	0.67
7950 Berezov	11.40	0.0663	0.011	27.10	2.0	0.10	3	3	0.38
7965 Katsuhiko	12.00	0.0634	0.010	21.02	1.5	0.10	2	2	1.00
7979 1978 SV7	13.00	0.0493	0.009	15.03	1.2	0.10	2	2	0.25
7994 Bethellen	12.50	0.0391	0.009	21.26	2.1	0.10	1	2	0.33
7999 Nesvorny	12.00	0.0629	0.010	21.09	1.5	0.10	4	5	1.00
8062 1977 EZ	12.60	0.0718	0.026	14.99	2.1	0.81	2	4	1.00
8157 1988 XG2	13.20	0.0545	0.016	13.04	1.6	0.10	1	2	0.25
8223 Bradshaw	13.70	0.0302	0.005	13.92	1.0	0.10	2	3	0.33

Asteroid	H	p_H	σp_H	D	σ_D	PLC	US	UO	FOR
8259 1983 UG	14.10	0.1120	0.020	6.01	0.5	0.10	2	3	0.20
8292 1992 SU14	12.20	0.1680	0.032	11.77	1.0	0.10	1	2	0.17
8354 1989 RF	12.60	0.0457	0.009	18.78	1.6	0.10	2	2	0.40
8380 Tooting	12.00	0.1903	0.022	12.13	0.6	0.10	4	5	0.57
8449 1977 EO1	12.90	0.0312	0.008	19.79	2.1	0.10	1	2	0.13
8486 1989 QV	13.00	0.0201	0.004	23.53	2.1	0.10	2	2	0.25
8487 1989 SQ	13.40	0.0639	0.010	10.98	0.8	0.10	3	4	0.38
8579 1996 XV19	13.60	0.0313	0.007	14.31	1.3	0.10	1	2	0.25
8701 1993 LG2	12.70	0.0459	0.010	17.89	1.6	0.10	2	2	0.50
8721 AMOS	11.20	0.0235	0.004	49.91	3.7	0.10	2	5	0.25
8737 1997 AL13	12.00	0.0621	0.011	21.24	1.6	0.10	2	3	0.40
8802 1981 EW31	13.50	0.0238	0.005	17.21	1.6	0.10	2	2	0.17
8813 1983 WF1	11.90	0.1664	0.027	13.59	1.0	0.10	2	3	1.00
8823 1987 WS3	13.00	0.0831	0.012	11.58	0.7	0.10	2	4	1.00
8861 Jenskandler	13.50	0.0147	0.003	21.86	2.0	0.10	1	2	0.17
8889 1994 OC	11.60	0.0727	0.028	23.59	3.6	0.38	2	2	0.25
8891 1994 RC1	12.60	0.0553	0.006	17.07	0.9	0.10	5	9	0.71
8917 1996 EU2	11.30	0.0452	0.007	34.34	2.4	0.23	4	7	1.00
8951 1997 FO	11.80	0.0692	0.013	22.06	1.8	0.10	2	2	0.33
9003 1981 UW21	12.70	0.0326	0.006	21.22	1.8	0.10	2	2	0.40
9090 Chirotenmondai	12.50	0.0609	0.010	17.03	1.2	0.10	3	4	0.50
9107 1997 AE4	13.20	0.0255	0.005	19.07	1.7	0.10	2	2	0.17
9247 1998 MO19	12.10	0.0553	0.012	21.49	2.0	0.10	1	2	0.14
9294 1983 EV	13.10	0.0418	0.009	15.60	1.4	0.10	2	2	0.29
9344 Klopstock	14.30	0.0116	0.002	17.05	1.5	0.10	2	2	0.40
9347 1991 RY21	13.60	0.0509	0.011	11.23	1.0	0.10	1	2	0.06
9402 1994 UN1	12.30	0.0402	0.007	23.00	1.8	0.10	3	3	0.30
9515 1975 RA2	13.10	0.0738	0.023	11.74	1.5	0.10	1	2	0.50
9559 1987 DH6	13.20	0.0466	0.008	14.10	1.1	0.10	3	3	0.33
9661 1996 FU13	11.40	0.0745	0.011	25.56	1.7	0.10	4	5	0.67
9719 1977 DF2	13.40	0.0197	0.005	19.77	1.9	0.10	2	2	0.33
9799 1996 RJ	9.90	0.0460	0.005	64.87	3.1	0.10	4	6	0.67
9920 1981 EZ10	13.60	0.0270	0.006	15.42	1.4	0.10	2	2	0.40
10046 1986 JC	13.60	0.0418	0.005	12.40	0.7	0.10	3	4	1.00
10050 1987 MA1	13.30	0.0722	0.015	10.82	1.0	0.10	2	2	0.50
10227 1997 VO6	12.20	0.0325	0.006	26.79	2.3	0.10	2	2	0.50
10259 1972 HL	12.30	0.0523	0.006	20.16	1.1	0.15	4	8	0.67
10287 1982 UK7	13.40	0.0602	0.021	11.32	1.6	0.48	2	3	0.20
10288 1983 WN	14.60	0.0546	0.010	6.84	0.6	0.10	1	2	0.50
10291 1985 UT	11.80	0.0489	0.007	26.24	1.6	0.10	4	5	0.57
10299 1988 VS3	13.20	0.0706	0.011	11.46	0.8	0.10	2	3	0.33
10328 1991 GC1	14.10	0.0519	0.010	8.83	0.8	0.10	1	2	0.08
10369 1995 CE2	12.90	0.0529	0.010	15.20	1.3	0.10	3	4	0.30
10386 1996 TS15	12.00	0.0611	0.011	21.41	1.7	0.10	2	3	0.29
10583 1995 WC4	11.90	0.0485	0.010	25.16	2.2	0.75	6	15	1.00
10637 1998 QP104	12.60	0.0241	0.007	25.84	2.9	0.10	1	2	0.11
10672 1978 QE	11.70	0.0719	0.011	22.66	1.5	0.10	4	5	1.00
10714 1983 QG	13.20	0.0778	0.019	10.91	1.1	0.96	8	17	0.89
10748 1989 CE8	13.00	0.0522	0.015	14.61	1.7	0.10	1	2	0.50
10766 1990 UB1	12.00	0.0354	0.006	28.13	2.1	0.10	4	4	0.67
10784 1991 RQ11	13.40	0.0309	0.008	15.79	1.8	0.10	1	2	0.25
10889 1997 AO1	11.50	0.0403	0.008	33.20	3.0	0.10	2	2	0.50

Asteroid	H	p_H	σp_H	D	σ_D	PLC	US	UO	FOR
10944 1999 FJ26	13.10	0.0412	0.005	15.71	0.8	0.10	4	5	0.67
10946 1999 HR2	13.00	0.0435	0.005	16.01	0.8	0.10	3	6	1.00
11004 1980 FJ1	12.20	0.0396	0.005	24.24	1.5	0.10	2	3	1.00
11096 1994 RU1	12.90	0.0697	0.016	13.25	1.3	0.10	2	2	0.29
11179 1998 FB109	13.70	0.0161	0.004	19.04	1.8	0.10	2	2	0.29
11195 1999 AY22	14.00	0.0329	0.007	11.62	1.1	0.10	1	2	0.14
11221 1999 JO26	12.20	0.0703	0.017	18.20	1.8	0.10	1	2	0.25
11232 1999 JA77	12.60	0.0264	0.010	24.71	3.7	0.37	2	2	0.29
11313 1994 GE10	14.10	0.0127	0.003	17.88	1.7	0.10	2	2	0.25
11351 1997 TS25	10.50	0.0627	0.014	42.16	4.0	0.10	2	2	0.50
11386 1998 TA18	13.60	0.0458	0.009	11.84	1.0	0.10	2	2	0.15
11395 1998 XN77	9.50	0.0669	0.007	64.71	3.1	0.10	4	7	1.00
11396 1998 XZ77	10.50	0.0469	0.009	48.73	4.2	0.10	2	2	0.40
11542 1992 SU21	11.30	0.0216	0.005	49.72	5.3	0.14	2	2	0.40
11569 Virgilsmith	12.00	0.0305	0.003	30.31	1.5	0.19	4	10	0.80
11576 1994 CL	13.30	0.0496	0.024	13.05	2.3	0.58	2	2	0.29
11645 1997 BY1	13.40	0.0988	0.019	8.84	0.7	0.10	3	3	0.38
11990 1995 WM6	13.50	0.0593	0.012	10.89	0.9	0.10	2	2	0.33
12003 1996 FM5	12.20	0.0276	0.006	29.07	2.7	0.10	1	2	0.33
12080 1998 FC111	12.30	0.0356	0.010	24.42	2.7	0.10	1	2	0.14
12098 1998 HV122	12.80	0.0422	0.006	17.81	1.2	0.10	2	3	0.33
12365 1993 YD	12.70	0.0194	0.004	27.53	2.6	0.10	2	2	0.29
12444 1996 GE19	10.10	0.0390	0.030	64.31	15.8	0.84	2	2	0.40
12445 1996 HE2	12.70	0.0278	0.006	22.99	2.0	0.10	2	2	0.15
12481 1997 EW47	13.40	0.0409	0.008	13.73	1.2	0.10	2	3	0.33
12583 1999 RC35	12.30	0.0320	0.011	25.76	3.6	1.00	4	10	0.67

Appendix 3. REPRINTS

Cellino, A., Di Martino, M. Egan, M. Price, S. D., Tedesco, E. F. (2000). Space-based infrared/visible telescope to study small solar system objects. *Proceedings of SPIE* Vol. 4013, pg. 68. Astronomical Telescopes and Instrumentation 2000 session on UV, Optical, and IR Space Telescopes and Instruments, 29-31 March 2000 in Munich, Germany.

We investigate broad system design and performance trades for a space-based infrared /visible telescope in study and discovery asteroids and comets in the solar system. The system design is driven by the requirements to obtain measurements that are more efficiently done from space. The mission objectives are to obtain accurate diameters and albedos for the known asteroids with a priority for the Near Earth Objects and to conduct and Aten search, completing the census within five years. Observations with an infrared spectrometer improve to 10% the accuracy in the derived diameter of the object and provide additional information on the composition. A rather modest sized telescope is found to be able to meet these objectives. The baseline system is a clear aperture, off-axis telescope with a 40 by 70 cm elliptical primary. The focal plane instruments consist of a large format visible CCD array, for measurement visible brightness and positions, and two Si:Ga infrared arrays for 6-11 um and 11-18 um radiometry. Thermal requirements are met with a closed cycle cryocooler and radiative cooling.

Egan, M.P.; Price, S. D.; and Tedesco, E. F. (1998). Infrared Detection and Characterization of Near Earth Objects. *Bull. American Astron. Soc.* **30**, #16.05

Infrared detection from space offers an invaluable adjunct to ground based visible searches for the discovery and characterization of Near Earth Objects (NEOs). The known Near Earth Objects are predominately highly reflective, presumably due to a discovery bias against dark objects inherent in visual surveys. For a given diameter, dark objects are at least a factor of four fainter in the visual than those with high albedo. Various analyses argue that the population of dark objects among the NEOs should be at least as great as the highly reflective objects. In the mid-infrared (defined to be between 5 and 35 mu m) the flux difference between high and low albedo objects is relatively small, with slightly more flux coming from the dark object. Passive emission from objects located in the inner solar system peaks in the mid-infrared as the natural consequence of the object being in thermal equilibrium with the incident sunlight An infrared NEO survey compensates for the bias of visible searches to preferentially discover high albedo objects. Additionally, visual to infrared colors of NEOs are markedly different from those of most stars. This provides a basis for a bulk filter that significantly reduces the onboard signal processing requirements for a space-based system. Infrared observations also reduce the uncertainty in estimating the size, and subsequently the mass, of an NEO. A geometric albedo must be assumed in order to calculate a diameter from the single band visual photometry obtained during discovery or follow-up astrometry. The estimated size is thus quite uncertain owing to the order of magnitude range in NEO geometric albedos. The modeling assumptions needed to convert an infrared observation into a diameter are more tightly constrained. An infrared observation combined with visual photometry provides the requisite information to accurately determine both the albedo and size. Since the estimate of the NEO mass depends on volume, the determinations of NEO mass from infrared derived diameters are about an order of magnitude more certain than that estimated from visible photometry.

Sykes, M. V.; Cutri, R. M.; Fowler, J. W.; Tholen, D. J.; Skrutskie, M. F.; Price, S.; Tedesco, E. F. (2000). The 2MASS Asteroid and Comet Survey. *Icarus* **146**, 161-175.

A reprint of this paper was unavailable at the time the final report was written. Below is the paper's abstract obtained from the ADS Astronomy Abstract Service.

Over the course of three years, the Two Micron All Sky Survey (2MASS) will carry out a survey of the entire sky at J (1.25 μm), H (1.65 μm), and K_s (2.17 μm) from telescopes in the northern and southern hemispheres. The initial public release of the survey data spans the period between June 7, 1997, and January 30, 1998, and covers approximately 6% of the sky. Asteroids and comets having known orbits were identified on the basis of their predicted positions as part of the pipeline processing of the data. The 2MASS sources associated with asteroids and comets are being compiled into a 2MASS Asteroid Catalog and 2MASS Comet Catalog. These catalogs are now available and will be updated at regular intervals as the survey progresses. The initial catalogs contain observations of 1054 asteroids and 2 comets, respectively. Near-infrared colors of asteroids of different taxa are shown, and an attempt is made to derive a simple compositional map of the asteroid belt, which is in agreement with previous work. The color-color distributions of Koronis asteroid family members are found to be distinct from those of other families in this sample. It is suggested that the Koronis parent body was differentiated and that different mineralogies had segregated on spatial scales much larger than 10 km prior to its catastrophic disruption. Two asteroids exhibiting unusual colors are examined, and a cautionary note is sounded about interpreting the colors of individual asteroids without considering the possibility of contamination by a background source.

Tedesco, E. F.; Muinonen, K.; Egan, M.P.; and Price, S. D. (1998). Discovery of Aten Asteroids: Visual Ground-Based vs. Infrared Space-Based. *Bull. American Astron. Soc.* **30**, #16.06

Aten asteroids are that sub-group of the Near-Earth Asteroid (NEA) population with semimajor axes < 1 AU and aphelia > 0.983 AU. As of 1998 May 24, the observed population is 502, 6% of which are Atens. This is a lower-limit because search programs observe primarily around the opposition point and, for a given size and albedo, Atens are generally fainter than other NEAs at discovery. Thus the Aten population is being seriously under-sampled in current search programs.

If the Aten population is about 25% that of the Apollo population, then their hazard potential is about half that for the Apollos because the impact probability with the Earth for an Aten is twice that for an Apollo (Bottke, *et al.*, 1994, Hazards due to Comets and

Asteroids, p. 337, T. Gehrels, ed.). Thus the under-sampling of this population is significant in terms of the goals of the NEO hazard search program.

According to Bowell and Muinonen (*Ibid.*, p. 149) it would require 25 years to discover 33% of the Aten population, with diameters larger than 0.5 km, if a 6,000 sq deg/month area within 30 degrees of opposition were searched to V < 22. This would increase to 83% by searching the same area more broadly in longitude. Current surveys cover a few thousand square degrees of sky per month to V ~ 20 and a few hundred square degrees to fainter limiting magnitudes.

Preliminary results of our simulations show that a space-based infrared system would discover (and characterize) over 90% of Atens larger than 0.5 km in a five-year period.

Tedesco, E. F.; Muinonen, K.; Price, S. D. (2000). Space-based infrared near-Earth asteroid survey simulation. *Planet. Space Sci.* **48**, 801-816.

See attached.

Appendix 4 - Bias Correction

i = Spatial zones

i

0 a < 2.10 and e > 0.18 Mars Crossers (Not dealt with in this study)
1 a >= 1.85 and < 2.10 and e <= 0.18 Hungaria Group
2 a >= 2.10 and < 2.50
3 a >= 2.50 and < 2.82
4 a >= 2.82 and < 2.95
5 a >= 2.95 and < 3.30
6 a >= 3.30 and < 3.75 "Cybeles"
7 a >= 3.75 and < 4.50 "Hildas"
8 a >= 4.50 "Trojans"

The "lost" asteroid 719 Albert (recovered in 1999) was dealt with by setting its a to 2.0 and its e to 0.50 in BiasCorInput.txt This causes it to be rejected as a Mars Crosser.

j = Apparent opposition mag (Va0) bin

From R. Jedicke and T. S. Metcalfe (1998, The orbital and absolute magnitude distributions of main belt asteroids,Icarus 131, 245-260) I converted the completeness limiting absolute magnitudes for the three regions into which they divided the main belt (<a>, H: 2.30, 12.75; 2.80, 12.25; 3.25, 11.25) to mean opposition magnitudes (<a>, Va0: 2.30, 15.13; 2.80, 15.76; 3.25, 15.57) or, 15.50 +/- 0.25. Hence, N_{ij} is essentially complete for j < 19. This limit is also that obtained by Zappalà, V. and Cellino, A. (1996).

j	Va0	N_{ij}	n_{ij} 27	n_{ij} 17	BF 27	BF 17	N_{ij}	n_{ij} 27	n_{ij} 17	BF 27	BF 17
7	[9.75 - 10.25)										
8	[10.25 - 10.75)		0.5 mag bins					1.0 mag bins			
9	[10.75 - 11.25)										
10	[11.25 - 11.75)										
11	[11.75 - 12.25)										
12	[12.25 - 12.75)	1	1	1	1.000		1	1	1	1.000	1.000
13	[12.75 - 13.25)	2	0	0							
14	[13.25 - 13.75)	8	5	4	1.600	2.000	10	5	4	2.000	2.500
15	[13.75 - 14.25)	15	9	6	1.667	2.500					
16	[14.25 - 14.75)	29	5	2	5.800	14.500	44	14	8	3.143	5.500
17	[14.75 - 15.25)	33	4	3	8.250	11.000					
18	[15.25 - 15.75)	24	3	1	8.000	24.000	57	7	4	8.143	14.250
19	[15.75 - 16.25)	9									
20	[16.25 - 16.75)	3					12	0	0		

Albedo classes

From (>)	Albedo class	To (≤)	Logarithmic Mean
	low	0.089	0.0501 (assuming lower bound is 0.0282)
0.089	intermediate	0.112	0.1000
0.112	moderate	0.355	0.1995
0.355	high		0.4467 (assuming upper bound is 0.5623)

The above Logarithmic Mean values were checked against the mean and median values of the non-family asteroid sample with radiometrically derived albedos and was found to be in agreement. The means/medians for the four albedo classes are: 0.0547/0.0533, 0.0990/0.0986, 0.1974/0.1883, 0.4624/0.4364, respectively.

$BF(X)_{ij} = N_{ij}/n_{ij}$, where n_{ij} = the number of asteroids in spatial zone i and magnitude bin j having a measured albedo, and Nij is the total number in the same i, j bin. For j > 18 completeness corrections must then be applied.

For the sample (17) with radiometric albedos (Actual/Bias-Corrected):

j	BF	L	I	M	H	Total
11 + 12	1.000		0		1/1	1
13 + 14	2.500		0	2/5	2/5	4
15 + 16	5.500	1/5.5	0	5/27.5	2/11	8
17 + 18	14.250	1/14.25	0	0	3/42.75	4

For the sample (27) with radiometric+ "best guess" albedos (Actual/Bias-Corrected):

j	BF	L	I	M	H	Total	
5 + 6	1.000		0		1/ 1	1	
7 + 8	2.000		0	3/ 6	2/10	5	
9 + 10	2.714	1/2.71	0	8/21.71	5/13.57	14	55
11 + 12	8.143	1/8.14	0	3/24.43	3/24.43	7	112

Hungaria Group Albedo Distribution (in %)

(Rad = Sample with radiometric albedos; All Obs = Sample with radiometric, or best-guess class, or B-V based albedos; Bias Cor. = Bias-corrected sample combining all magnitude bins; Adopted = the distribution adopted for use in this study; Num in 8603 set = Number of Hungaria asteroids in each albedo class for the asteroids numbered through 8603)

Albedo j	Rad Obs <11	Rad Obs <13	All Obs <11	All Obs <13	Bias Cor Rad <11	Bias Cor Rad <13	Bias Cor All <11	Bias Cor All <13	Adopted %	Adopted Num in 8603 set
L	8	12	5	7	10	18	5	9	10	12
I	0	0	0	0	0	0	0	0	0	0
M	54	41	55	52	59	29	50	47	50	62
H	38	47	40	41	31	53	45	44	40	50

Zone 2

j	Va0	N_{2j} 2228	n_{2j} 235	BF	L	I	M	H
1	[6.75 - 7.25)							
2	[7.25 - 7.75)							
3	[7.75 - 8.25)	1	1	1			1	
4	[8.25 - 8.75)	1	1	1			1	
5	[8.75 - 9.25)	2	2	1			2	
6	[9.25 - 9.75)	4	3	1.333			3/ 4	
7	[9.75 - 10.25)	8	8	1	1	1	6	
8	[10.25 - 10.75)	5	5	1			5	
9	[10.75 - 11.25)	9	9	1	4		5	
10	[11.25 - 11.75)	13	13	1	2	2	9	
11	[11.75 - 12.25)	14	14	1	4	1	9	
12	[12.25 - 12.75)	15	13	1.154	5/ 5.77	1/ 1.15	5/ 5.77	2/ 2.31
13	[12.75 - 13.25)	18	15	1.200	5/ 6		9/10.80	1/ 1.20
14	[13.25 - 13.75)	25	20	1.250	10/12.50	2/ 2.50	8/10.00	
15	[13.75 - 14.25)	44	25	1.760	6/10.56	2/ 3.52	13/22.88	4/ 7.04
16	[14.25 - 14.75)	89	30	2.967	10/29.67	3/ 8.90	15/44.50	2/ 5.93
17	[14.75 - 15.25)	216	31	6.968	17/118.46		13/90.58	1/ 6.97
18	[15.25 - 15.75)	456	18	25.333	<-- Incompletness begins; BF too big			

Albedo i=2 j	Rad Obs	Rad %	Bias Cor Obs	Bias Cor %	Adopted Cor %
L	47	(29.56)	75.50	30.44	45
	64	(33.68)	193.96	41.80	
I	12	(7.55)	20.07	8.09	5
	12	(6.32)	20.07	4.33	
M	91	(57.23)	135.95	54.82	45
	104	(54.74)	226.53	48.82	
H	9	(10.36)	16.48	6.65	5
	10	(5.26)	23.45	5.05	

Zone 3

j	Va0	N_{3j} 1664	n_{3j} 528	BF	L	I	M	H
1	[6.75 - 7.25)	1	1	1		1		
2	[7.25 - 7.75)							
3	[7.75 - 8.25)	1	1	1			1	
4	[8.25 - 8.75)	1	1	1			1	
5	[8.75 - 9.25)	2	2	1			2	
6	[9.25 - 9.75)	4	3	1.333			3/ 4	
7	[9.75 - 10.25)	8	8	1	1	1	6	
8	[10.25 - 10.75)	5	5	1			5	
9	[10.75 - 11.25)	9	9	1	4		5	
10	[11.25 - 11.75)	13	13	1	2	2	9	
11	[11.75 - 12.25)	14	14	1	4	1	9	
12	[12.25 - 12.75)	15	13	1.154	5/ 5.77	1/ 1.15	5/ 5.77	2/ 2.31
13	[12.75 - 13.25)	18	15	1.200	5/ 6		9/10.80	1/ 1.20
14	[13.25 - 13.75)	25	20	1.250	10/12.50	2/ 2.50	8/10.00	
15	[13.75 - 14.25)	44	25	1.760	6/10.56	2/ 3.52	13/22.88	4/ 7.04
16	[14.25 - 14.75)	89	30	2.967	10/29.67	3/ 8.90	15/44.50	2/ 5.93
17	[14.75 - 15.25)	216	31	6.968	17/118.46		13/90.58	1/ 6.97
18	[15.25 - 15.75)	456	18	25.333	<-- Incompleteness begins; BF too big			

Albedo i=2 j	Rad Obs	Rad %	Bias Cor Obs	Bias Cor	%
L	47	(29.56)	75.50	30.44	42
	64	(33.68)	193.96	41.80	
I	12	(7.55)	20.07	8.09	4
	12	(6.32)	20.07	4.33	
M	91	(57.23)	135.95	54.82	49
	104	(54.74)	226.53	48.82	
H	9	(10.36)	16.48	6.65	5
	10	(5.26)	23.45	5.05	

Appendix 5 – Creation of the Asteroid Family Statistical Models

The total CPU time required to produce statistical models for all 15 of the major asteroid families, using a 300 MHz Pentium II PC, was 167 hours.

The mean albedo, on which the Gaussian distribution was centered, and the number of asteroids from which it was computed are given in Table 1.

Details on each of the 15 major families, including the seed used in processing them, is given in Table 2.

Table 1. Adopted Albedos.

Adopted Albedo	Remarks (Mean of . . .)
0.0798	11 Adeona members
0.0577	8 Dora members
0.1389	96 Eos members
0.0543	3 Erigone members
0.1897	21 Eunomia members
0.2109	41 Flora members
0.1046	4 Gefion members
0.0787	8 Hygiea members
0.2078	25 Koronis members
0.2145	18 Maria members
0.2096	ZERO Massalia members
0.2207	ZERO Merxia members
0.0811	104 Themis members
0.0694	5 Veritas members
0.2800	2 Vesta members

Table 2. Families Processed

Family (Parent Body Diam in km)	Run Time (sec)	No. Input (D > 1 km)	No. Rej. (Out of MB, imp e, i>90, MCs, JCs)	No. Accepted	Num, Un-num, Syn	Remarks (Seed; K)
Adeona (189)	2,691	100,000	18 (3; 0; 0; 15; 0)	99,983	15; 48; 99,920	(456; 1.60) Dmin=2.49
Dora[6] (88)	170	24,000	0	24,000	7; 70; 23,923	(789; 1.35) Dmin=2.65
Eos (218)	7,173	162,000	58,253 **(36280; 21622; 0; 351; 0)**	103,747	191; 286; 103,270	(987; 1.42) Dmin=4.26
Erigone (91)	98	16,000	1,398 (18; 0; 0; 1380; 0)	14,602	5; 40; 14,557	(654; 1.60) Dmin=1.36
Eunomia[7] (284)	278,920	1,000,000	440,977 **(258,747; 90,244; 0; 91,986; 0)**	559,023	127; 436; 558,460	(321; 1.65) Dmin=1.22
Flora (164)	529	30,000	11,731 (8676; 1148; 0; 1907; 0)	18,269	268; 551; 17,450	(123; 1.50) Dmin=1.00
Gefion (74)	77	12,000	0	12,000	13; 73; 11,914	(1234; 1.32) Dmin=2.37
Hygiea (481)	47	10,000	5,173 (4,061; 693; 0; 419; 0)	4,827	8; 95; 4,724	(5678; 1.55) Dmin=3.43
Koronis (119)	586	46,000	10,653 (3,067; 7,582; 0; 4; 0)	35,341	55; 270; 35,022	(4321; 1.32) Dmin =2.04
Maria (130)	152	21,000	5,507 (2,857; 2,326; 0; 324; 0)	15,493	55; 65; 15,373	(987; 1.30) Dmin=1.57
Massalia (151)	2,753	100,000	0	100,000	4; 45; 99,951	(432; 2.10) Dmin=1.0
Merxia (42)	24	2,500	0	2,500	8; 17; 2475	(543; 1.45) Dmin=1.29
Themis (369)	274,779	1,000,000	542,650 **(431,067; 65,554; 0; 46,038; 0)**	457,350	317; 233; 456,800	(678; 1.45) Dmin=3.03
Veritas (167)	74	6,000	233 (233; 0; 0; 0; 0)	5,767	8; 14; 5,745	(910; 1.55) Dmin=5.79
Vesta (468)	34,293	350,000	63,328 **(42,300; 15,332; 0; 5,696; 0)**	286,672	49; 181; 286,442	(873; 2.10) Dmin=1.0
Summary:	602,366	2,879,500		1,739,574		

Fig. 1, below, uses the Themis family to illustrate the importance of using randomly assigned albedos, rather than the mean albedo, for family members or background asteroids lacking a measured albedo. The mean albedo for the Themis family is 0.0811; Fig. 1 shows the actual albedo distribution for the fainter Themis family members.

6 Also ran using seeds 123 and 456. Results in both cases were the same as the original; no objects were rejected.

7 Unnumbered members: 1978 NF, 1988 BG (not a valid provisional designation according to the MPC), 1990 HH1, 1990 QR, 1990 UA1, 1991 XU (9191).

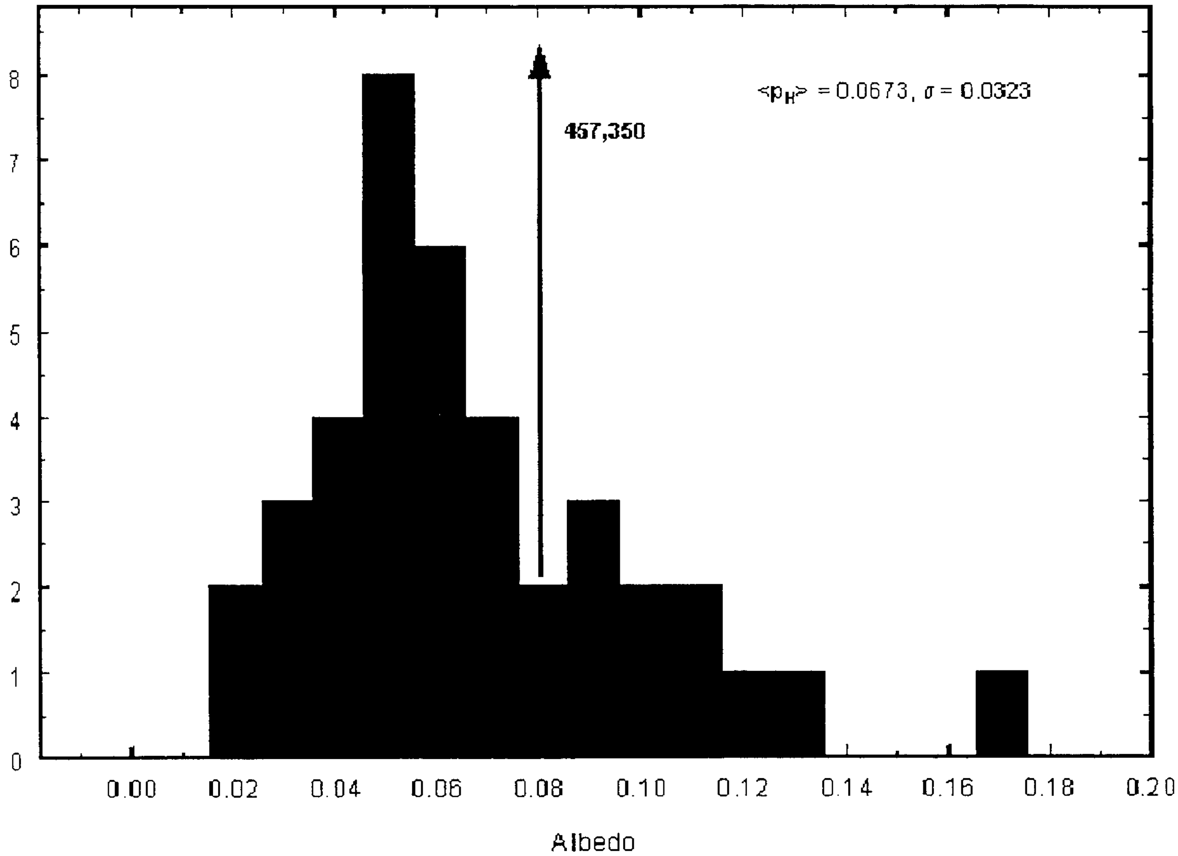

Fig. 1. Albedo Histogram for Themis Family Asteroids with Va0 > 15.74.

Note that the mean for these 35 smaller Themis family asteroids is only 0.0673 and that they are distributed (mostly) from 0.02 to 0.13. While this distribution does not appear to be especially "normal", still a normal distribution with mean 0.0673 and standard deviation 0.0323 will better match the observed distribution than to assign an albedo of 0.0811 to all 457,350 statistical members.